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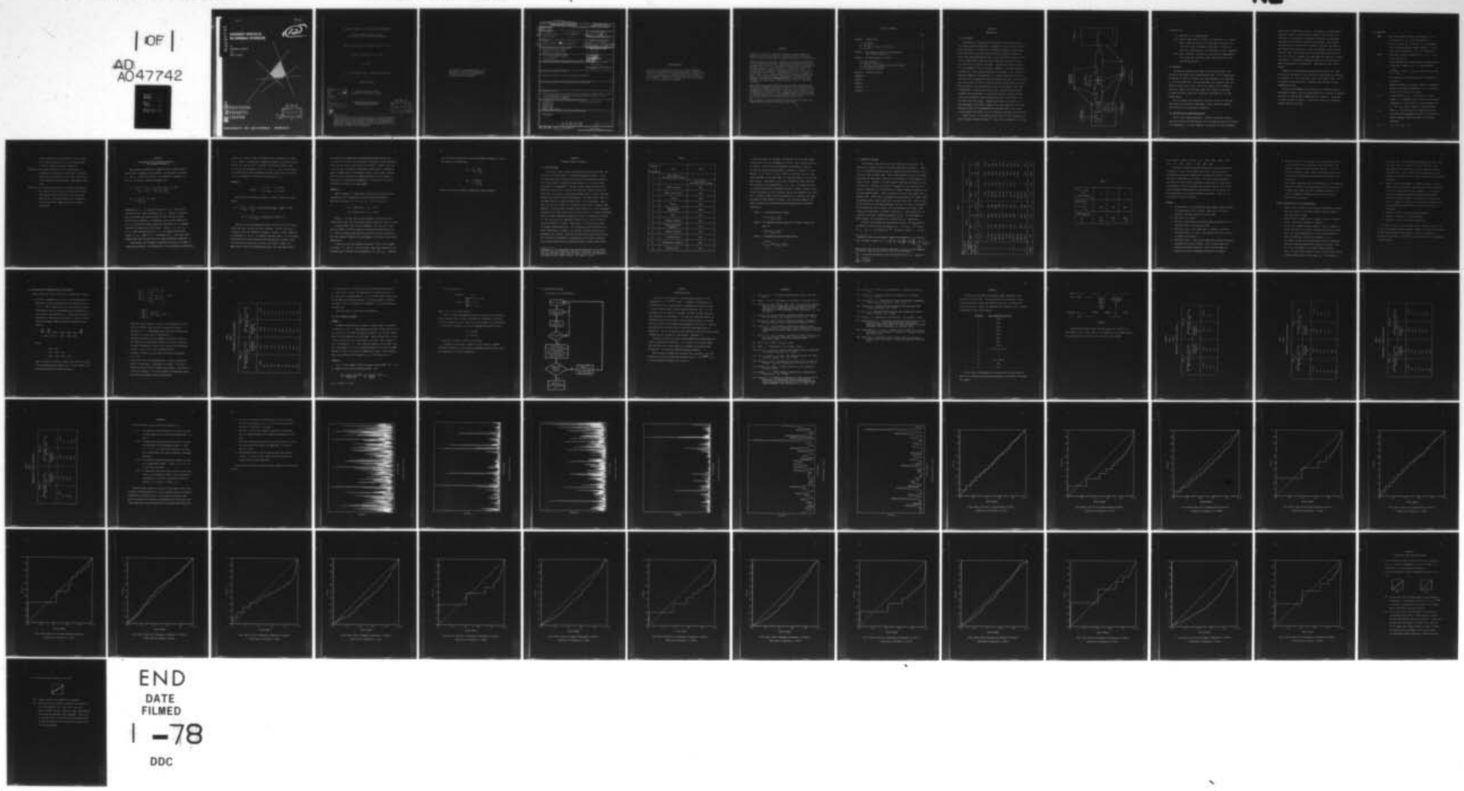

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AVAILABILITY ANALYSIS OF THE SUPERHILAC ACCELERATOR

by
RICHARD E. BARLOW
and
TOM Y. LIANG

OPERATIONS
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AVAILABILITY ANALYSIS OF THE SUPERHILAC ACCELERATOR[†]

Analysis of Two Years of Operating
Data from the Lawrence Berkeley Laboratory

Operations Research Center Research Report No. 77-21

Richard E. Barlow and Tom Y. Liang

July 1977

U. S. Army Research Office - Research Triangle Park

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Operations Research Center
University of California, Berkeley

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ABSTRACT

Records of 26 months of operating, repairing, and maintaining the nuclear accelerator Superhilac at the Lawrence Berkeley Laboratory (LBL) are analyzed with respect to system availability and reliability.

A major portion of the report is devoted to building a suitable model for the availability analysis. Some specific recommendations for improvement are also given. The current availabilities for operating the machine in Modes 1, 2, and 3 are 64.8%, 76.9%, and 80% respectively. The Adam injector is most responsible for causing the current low availability level of Mode 1. An increase of 15 hours on top of the current MTBF of 22.74 hours for the Adam injector (*or*, a decrease of about 2 hours from its current MTTR of 5.15 hours) would result in an overall boost of 5.6% for Mode 1 availability. ~~(See Chapter 3 and Appendix 2 for additional recommendations.)~~ Either way, this would translate into about 6 more usable hours every 4 days of operations for Mode 1.

Some optimization schemes (when the costs associated with improving the various equipments are known) are indicated for obtaining specific adjustments to be made systemwide in order to achieve economically an assigned higher availability level. Such models and schemes can easily be adapted to future needs as the information gathering system evolves in the near future into an organic computer network capable of collecting and analyzing much more voluminous and accurate data.

Also included are system reliability and miscellaneous findings from Time Series Analysis and Total Time on Test Plots.

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CHAPTER 1

INTRODUCTION

1.1 The System

The system to be studied is the Superhilac nuclear accelerator at the Lawrence Berkeley Laboratory, a diagram of which is shown in Figure 1. As in the figure, it consists of 14 different categories of subsystems. This comes from the way the failure data are recorded and classified. Notice that some subsystems are more or less well defined physical blocks, like the Adam and Eve injectors, while others are spread over some or all portions of the entire accelerator. Subsystem 14 (building power) is a good example of such a subsystem. Needless to say, each subsystem so defined is a very sophisticated piece of equipment. Also, despite its physical appearance, the Superhilac is a series system since failure of any one of the 14 subsystems causes the system to go down. As can be seen, the entire journey of the ion beams starts from the injection area, where various types of ions are prepared and injected according to the needs of experiments. Entering the second region, composed of pre-stripper, stripper, and post-stripper, the particles gain more and more momentum as they are stripped of their orbiting electrons in the carefully set and tuned electrical fields. Bending and turning as directed by the steering magnets, they finally emerge at the exit, where they are either delivered directly to the experimenters requesting them or are transported through the transfer line to be further accelerated by the Bevatron.

Another account of the system from the point of view of mathematical model building is given in Chapter 3. Here, for our purposes, it suffices

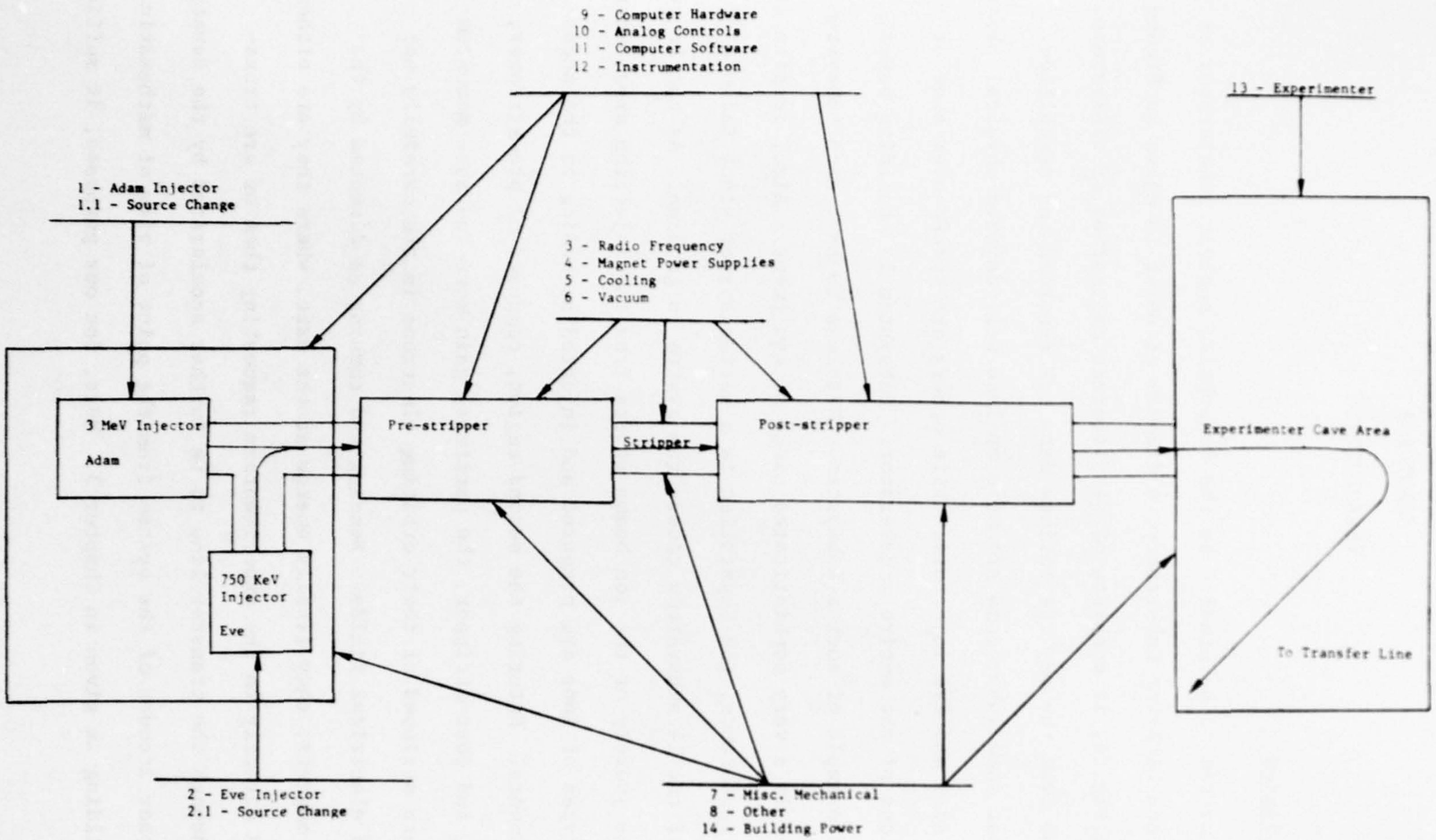


FIGURE 1

SUBSYSTEMS OF THE SUPERHILAC

to mention that

(i) basically it is a series system;

(ii) when the Adam injector is used in the operation, it is called Mode 1; when Eve is used it is called Mode 2; finally, when a fraction of the ion beams of either Mode 1 or Mode 2 is taken for a third group, it is called Mode 3, alias, "parasitic";

(iii) Mode 1 and Mode 2 ion beams can be accelerated independently at the same time through the same structure because of the time-sharing facility.

1.2 The Data

The data was compiled by Lee Besse [9] from log books kept over the period from *January 1974 through February 1976.* As the system fails, the failure is traced, according to the best knowledge of the repairmen, to the villain subsystem. The operating mode, the occurrence time, the number of repair hours, the up time so far recorded for the system, as well as the name of the subsystem, among other things, are recorded. As mentioned before, there are 14 different subsystems that can cause system failure.

For our purpose, the quantities of interest are the up times and down times of the system and subsystems. The way these are computed from the data book is explained in Appendix 1.

1.3 The Need for the Study and the Goal

LBL is a world famous laboratory. Groups of scientists come not only from all over the United States, but also from many parts of the world, to do experiments. As can be imagined, not everyone can get experimental

time by merely submitting a proposal. There exists a Program Advisory Committee, formed of leading nuclear scientists, which oversees the utilization of the machine by examining the proposals and assigning time based on the scientific worth of each proposal. An occasional interruption of a few hours can of course be tolerated, but longer or more frequent interruptions are a great inconvenience to the group(s) involved. Also, the potential use of the very high energy heavy ions as a tool for cancer treatment also underlines the importance of higher availability. Consequently, systematic efforts are now being made to improve availability and reliability. This study is a part of such efforts.

Roughly, the current system availabilities are about 70%. That is to say, in the long run, there are only 70 usable hours per 100 hours of operation, or a little more than a day is lost every 4 days. It is the opinion of LBL people that a desirable level should be in the neighborhood of 95%.

The plan of development of this report is to introduce some preliminaries in Chapter 2 and then build models for our system, do analyses, and spell out some specific recommendations in Chapter 3. Reliability is briefly treated in Chapter 4. We end this chapter by listing the notation used in this study.

1.4 Notation

MTBF: Mean time between failures, also denoted by μ for the system or by μ_i for the ith subsystem i. Most of the time, the μ and the μ_i are estimated from the operating data by simple averaging. In this case, they are denoted by $\hat{\mu}$ or $\hat{\mu}_i$ respectively.

MTTR: Mean time to repair is denoted by v, v_i or $\hat{v}$, $\hat{v}_i$ as the case may be.

A : System availability in general is the limiting fraction of time that a system is up. It is estimated by

$$\frac{\sum u_j}{\sum u_j + \sum d_j}$$

, where u_j and d_j are the jth up times and down times in a fairly long period of operation of the system.

$A_{\cdot\cdot}$: System availability of a series system of 2 components, which are functionally independent, i.e., the failure of one will not shut off the other.

$A_{n\cdot\cdot}$: A generalization of $A_{\cdot\cdot}$ to the case of a series system of n components, each of which is structurally independent of all the others. We will sometimes write $A_{\cdot\cdot}$ for $A_{n\cdot\cdot}$ when no danger of confusion exists.

$A_{\leftrightarrow}$: Like $A_{\cdot\cdot}$, but now failure of *either* one turns off the other, thus suspending the useful life of the non-failed component during the repair of the failed component.

$A_{n\leftrightarrow}$: $A_{n\leftrightarrow} : A_{\leftrightarrow} = A_{n\cdot\cdot} : A_{\cdot\cdot}$.

R : System reliability is the probability that a system will perform satisfactorily for an assigned length of time or longer under stated conditions.

Assumption: The random lifetimes of all the subsystems (or components) for any model in this report are assumed *statistically independent* of each other. This is not to be confused with the functional independence stated above.

Convention: All % values are absolute, not relative unless otherwise stated. That is to say, if one system achieves 78% availability and another 80%, then we say they differ by 2%. But since typically our availability will be about 70% or higher this is not a serious distinction.

CHAPTER 2

TWO-COMPONENT SERIES SYSTEM AVAILABILITY - TWO PLEASANT PROPERTIES

Many features pertaining to 2-component series systems readily carry over to n-component series systems. We presented the notation $A_{\cdot\cdot}$ and $A_{\leftrightarrow}$ in the last chapter. The formulas for computing $A_{\cdot\cdot}$ and $A_{\leftrightarrow}$ in terms of component parameters are:

$$A_{\cdot\cdot} = \frac{1}{1 + \frac{\nu_1}{\mu_1}} \cdot \frac{1}{1 + \frac{\nu_2}{\mu_2}} = \frac{1}{1 + \frac{\nu_1}{\mu_1} + \frac{\nu_2}{\mu_2} + \frac{\nu_1\nu_2}{\mu_1\mu_2}} \quad \text{(cf. [4])},$$

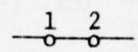
$$A_{\leftrightarrow} = \frac{1}{1 + \frac{\nu_1}{\mu_1} + \frac{\nu_2}{\mu_2}} \quad \text{(cf. [6])}.$$

Algebraically, $A_{\cdot\cdot}$ is less than or equal to $A_{\leftrightarrow}$. This is also intuitively clear, from the definition of $A_{\cdot\cdot}$ wherein one component may be operating unnecessarily while the other is being repaired. As the notation suggests, an intermediate case is easily imagined to be $A_{\rightarrow}$, for which the setup is such that the failure of one component shuts off the other, *but not vice versa*. Clearly, $A_{\cdot\cdot} \le A_{\rightarrow} \le A_{\leftrightarrow}$, as $A_{\rightarrow}$ saves lifetime relative to $A_{\cdot\cdot}$, but wastes lifetime with respect to $A_{\leftrightarrow}$. When $n = 3$, the formulas for $A_{\rightarrow}$ and other intermediate cases have been derived in [8], under exponential assumptions.

Unfortunately, as the number of components increases, the number of cases grows enormously. The derivation of the corresponding availabilities

becomes very tedious though not impossible under exponentiality assumptions. However, although exact formulas are useful in some applications, as when very high accuracy is required, the following example shows that we are very fortunate in that $A_{\cdot\cdot}$ and $A_{\leftrightarrow}$ are so close together for medium high and high availability systems. Hence, for our purposes it is not necessary to calculate the exact value by $A_{\rightarrow}$:

Example 1:



$$\nu_1 = 1 \text{ hr.} \quad , \mu_1 = 10 \text{ hrs.}$$

$$\nu_2 = 3 \text{ hrs.} \quad , \mu_2 = 20 \text{ hrs.}$$

We note that such values are similar to some of those of our real system.

$$A_{\cdot\cdot} = \frac{1}{1+\frac{1}{10}} \cdot \frac{1}{1+\frac{3}{20}} = \frac{1}{1+0.1+0.15+0.015} = \frac{1}{1.265} = 0.7905 ,$$

$$A_{\leftrightarrow} = \frac{1}{1+.1+\frac{3}{20}} = \frac{1}{1+0.1+0.15} = \frac{1}{1.25} = 0.8 .$$

Notice that the two denominators differ from each other by a second order term, which accounts for their closeness. We easily see that in n-component cases the situation is similar. Therefore, errors committed in estimating $A_{\rightarrow}$ by $A_{\leftrightarrow}$ are usually relatively small. So, in practical applications, we are not interested in using the exact formulas, since in the real world other types of errors, are likely to arise, e.g., model errors, data-collecting-handling errors, and other human errors.

With more fully-computerized data gathering-analyzing systems, the last two kinds of errors can be expected to diminish, leaving the model errors the only ones to worry about if they exist. However, since the entire process of analyzing the superhilac data involves a substantial amount of human effort, involving many people at many stages, we would like to see how sensitive the system availability is with respect to the errors in calculating the parameters. It turns out to be fairly insensitive, as shown in the next example:

Example 2:

Refer to Example 1. Assume that a 10% error has occurred in the estimation of *all* 4 parameters, all in the direction favoring A. That is, we now have $\nu_1' = 0.9$, $\nu_2' = 2.7$, $\mu_1' = 11$, $\mu_2' = 22$.

$$A'_{..} = 0.8233 \Rightarrow A'_{..} - A_{..} = 3.3\%$$

$$A'_{\leftrightarrow} = 0.8302 \Rightarrow A'_{\leftrightarrow} - A_{\leftrightarrow} = 3.02\% .$$

Indeed, A is very robust since in general a 10% error is considered rather high, and cancellations between errors are likely to occur.

To guard against model errors, needless to say, one has to check that the essence of the real system is captured by the model built for it. This is no simple task since the real world is always complicated. The final judgement depends on the performance of the model versus actual observations.

To sum up, we have two pleasant properties. First, in the ranges of concern, $A_{..}$ and $A_{\leftrightarrow}$ are very close. Hence they suffice for calculating cases in between the two extremes of $A_{..}$ and $A_{\leftrightarrow}$. Secondly,

they are fairly insensitive to errors in parameter estimation. We end the chapter by recording here

$$A_{n\cdot\cdot} = \prod_{i=1}^{n} \frac{1}{1 + \frac{\nu_i}{\mu_i}},$$

$$A_{n\leftrightarrow} = \frac{1}{1 + \sum_{i=1}^{n} \frac{\nu_i}{\mu_i}}$$

(again for any set of mutually independent random variables).

CHAPTER 3

SYSTEM AVAILABILITY ANALYSIS

3.1 Model Building

In the last chapter we have considered some theoretical models. We now turn to the real system. As briefly described in Chapter 1, from the way the data were recorded, and the way the subsystems were defined, it is only natural to regard the system basically as a series system consisting of 13 subsystems.* However, certain complications do exist. Basically, this is due to the fact that there are 3 modes in which the accelerator is used for accelerating different types of ions at different energy levels and for different experiments. For input, Mode 1 uses *only* the Adam injector to inject pertinent ions to the pre-stripper. Mode 2 uses *only* the Eve injector for its purposes, while Mode 3, rightly termed parasitic, utilizes either the Adam or Eve injector for its own experiments, although the ion types from the two injectors need *not* be always interchangeable for a given experiment requested by a group of experimenters in Mode 3. Now, the rest of the subsystems in Mode 1 are *all shared* by Mode 2, and also by Mode 3, of course. (See Table 1.) This fact alone makes an elegant treatment difficult: Do we regard the entire Superhilac as a whole consisting of all modes, or do we have 3 separate systems corresponding to the 3 modes? Either way we suffer from inherent difficulties. But in the end we compromise by considering the three modes separately in our model building effort, basically because it lends itself readily

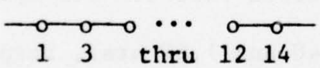
*Subsystem 13, the experimenter, has been excluded from all the models we built, since the system down time due to it has been restored to up time, for the system really has not failed. Moreover, the subsystem is not important since MTBF = 200 hrs. and MTTR = 1.5 hrs.

TABLE 1

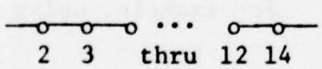
Subsystem \ System	Mode 1	Mode 2
1	Adam Injector (Including Source Change)	–
2	–	Eve Injector (Including Source Change)
3	Radio Frequency	Same
4	Magnet Power Supply	Same
5	Cooling	Same
6	Vacuum	Same
7	Miscellaneous Mechanical	Same
8	Other	Same
9	Computer Hardware	Same
10	Analog and Digital Hardware	Same
11	Computer Software	Same
12	Instrumentation	Same
13	Experimenter (Deleted)	Same
14	Building Power	Same

to simpler mathematical treatment, and because each of the three modes is peculiar to a set of experiments of its own - thus, separate study is of interest. We note here the fundamental shortcoming in doing so. Although the system considering Mode 1 by itself is a series of 12 subsystems 1, 3-12, and 14, it is not *completely isolated* in that at other times (sometimes at the same time) 11 of its subsystems are used by other modes as well. This makes it very hard to divide the loads (affecting the calculation and interpretation of $\hat{\mu}_i$'s and $\hat{\nu}_i$'s) among the modes. It is beyond the authors' knowledge to go into a further detailed account of what the system is, how it operates, and how the subsystems are classified. Instead, we shall present the results of our analysis, and judge the models by their ability to predict. Let us briefly summarize the models at hand and the shutting-off relationships between subsystems. [Appendix 1].

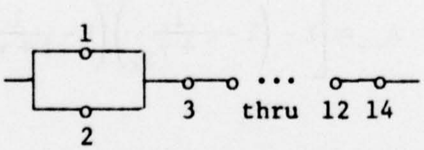
Mode 1: A 12-subsystem *series* system.



Mode 2: A 12-subsystem series system (11 of them are common with Mode 1).



Mode 3: A 13-subsystem parallel-series system.



3.2 Results of Analysis

The individual down times are easy to take from the data book. The individual up times are taken in the manner described in Appendix 1. Basically, the planned maintenance times are completely excluded from the calculation of up times and down times. Two up times separated solely by a planned maintenance up time and/or a period of no operation are pieced together as a single up time. Similarly, two down times so separated are added up to form one down time. Likewise, two pieces of component up time interrupted by a period of suspension due to the failure of a master component shutting it off are also lumped together. Table 2 is based on the data from January 1974 to February 1976. Notice that the parameters estimated under the 2 modes, where overlapping exists, usually agree with each other quite well. This is fairly strong evidence that the same subsystems 3-12 and 14 are used by both modes. The operating data kept for Mode 3 did not distinguish which mode it was riding on when both Mode 1 and Mode 2 were then up. This prevents the calculation of the mode 3 subsystem parameters values. Its system MTBF and MTTR, however, are calculated to be 6.40 and 1.60 hrs., respectively.

In Table 3 we recorded the availabilities obtained from system MTBF's and MTTR's, as well as from the formulas $A_{12\cdot\cdot}$ and $A_{12\leftrightarrow}$ (but written as $A_{\cdot\cdot}$ and $A_{\leftrightarrow}$ for simplicity).*,** For example, using $A_{\cdot\cdot}$ for Mode 1,

---

*Computed by using an approximation formula and estimating γ_i's from Mode 1 and 2 by simple averages, i.e., $A_{\leftrightarrow} \approx \left[1 - \left(1 - \frac{1}{1+\gamma_{11}}\right)\left(1 - \frac{1}{1+\gamma_{22}}\right)\right] \frac{1}{1 + \sum\limits_{\substack{i=3 \\ i\neq 13}}^{14} \frac{\gamma_{1i}+\gamma_{2i}}{2}}$.

Keep in mind that the ions of Mode 1 and Mode 2 are not all interchangeable for Mode 3. This should account for part of the discrepancy.

**$A_{\cdot\cdot}$ is calculated similarly, with the second factor in $A_{\leftrightarrow}$ changed to $\prod\limits_{\substack{i=3 \\ i\neq 13}}^{14} \frac{1}{1+\frac{\gamma_{1i}+\gamma_{2i}}{2}}$.

TABLE 2

Mode / Parameters / System & Subsystem	Mode 1				Mode 2			
	MTBF $\hat{\mu}$ or $\hat{\mu}_i$	MTTR $\hat{\nu}$ or $\hat{\nu}_i$	$\gamma_i = \frac{\hat{\nu}_i}{\hat{\mu}_i}$	A_i $\frac{1}{1+\gamma_i}$	MTBF $\hat{\mu}$ or $\hat{\mu}_i$	MTTR $\hat{\nu}$ or $\hat{\nu}_i$	$\gamma_i = \frac{\hat{\nu}_i}{\hat{\mu}_i}$	A_i $\frac{1}{1+\gamma_i}$
1	22.74	5.15	.2265	.815	-	-	-	-
2	-	-	-	-	24.70	1.61	.0652	.939
3	47.90	1.76	.0368	.965	55.50	2.23	.0402	.961
4	157.00	2.17	.0138	.986	165.00	1.31	.0079	.992
5	2098.17	1.00	.0005	1.000	861.10	1.93	.0022	.998
6	283.00	3.18	.0112	.989	273.00	3.29	.0121	.988
7	299.00	1.38	.0046	.995	142.00	1.47	.0104	.990
8	18.70	1.35	.0720	.933	17.60	1.46	.0830	.923
9	138.00	2.15	.0156	.984	155.00	2.13	.0137	.986
10	1549.75	1.00	.0006	.999	852.70	0.86	.0010	.999
11	6196.00	0	0	1	3413.30	1	.0003	1.000
12	3098.00	6.00	.0019	.998	6827.50	0	0	1
14	1259.30	2.38	.0019	.998	862.90	1.64	.0019	.998
System	5.94	3.22	.5421	.648	6.31	1.89	.2995	.769

TABLE 3

Availability \ Mode	1	2	3
From System $\hat{\mu}$, $\hat{\nu}$, i.e., $A = \dfrac{1}{1 + \frac{\hat{\nu}}{\hat{\mu}}}$	.648	.769	.800
Predictions of A by 2 methods $A_{\leftrightarrow}$ $A_{..}$	 .727 .698	 .808 .792	 .848* .842**

from the data of Table 2, we get: $.815 \times .965 \times .986 \times 1.000 \times .989 \times .995 \times .933 \times .984 \times .999 \times 1 \times .998 \times .998 = .698$.

If the models (together with the shutting-off relationships defined in Appendix 1 for the real systems) were correct, the actual system availabilities would fall somewhere in the intervals formed by the upper- and lower- bounds given by the models. But since they systematically fall below the lower bounds, the models (together with the shutting-off relationships for the real systems) are not quite correct. But in view of the extremely complex nature of the Superhilac, and in view of the following reasons, the difference between the actual A and $A_{..}$ of less than 5% is rather remarkable.

Remarks:

1. The Superhilac has been undergoing many changes, large and small, of various kinds [1,2,12, and 13]. Hence we are not really looking at the same system over the 26 months.
2. Data errors are present.
3. The actual shutting-off relationships among subsystems are not completely known, and change with time.
4. Coupling of Type 1: We repeat that for example, 3-12 and 14 are used by Mode 1, 2, and 3. Each system is not fully isolated as assumed in the models.
5. Coupling of Type 2: The lines of demarcation between the present subsystems are not well-defined. That is, there might exist overlapping between subsystems. This could invalidate the assumed statistical independence required by the models.

6. Whereas the more or less regular, 2-or-3-times-a-month maintenance probably helps a great deal, this intervention also causes the system to depart from model behavior. It is the intuitive feeling of people close to the system operation that right after the maintenance period the machine is more prone to failures.
7. Some limited simulation work [17] has shown that a 75% difference between the estimated system availability and the one given by an appropriate formula in terms of subsystem parameters for runs of a comparable length may easily be due to chance.
8. Others, known or unknown.

Further Consideration of the Above Remarks:

1. Remark 1 may be unimportant according to some people conversant with the system. It is a fair statement that the system by and large stays the same.
2. Remark 2 may be unimportant by a pleasant property of availability calculations considered in Chapter 2.
3. By the other pleasant property, Remark 3 could be unimportant if the true data do not differ substantially from the recorded data. It could become important if they differ drastically *since this seriously affects the estimation of* $\hat{\mu}_i$'s .
   As a matter of fact, we have experimented with the assumption that each component shuts off the others upon failure. Then the $\hat{\mu}_i$'s so obtained are so reduced that we obtained .654, .771, and .800 for Mode 1, 2, and 3 in that order from the formula predictions (of course using $A_{\leftrightarrow}$ to correspond to

this situation). What a remarkable agreement with .648, .769, and .800! Naturally, this does *not* prove that the actual shutting-off relationships are that each component shuts off everything else. But it underscores the importance of understanding the system well, for it might seriously affect parameter estimation.

4. & 5. Remark 4 is true and Remark 5 is likely to be true. They are likely able to account for a large portion of the discrepancies if the true reason does not lie in Remark 3. In the future, much more comprehensive automated record-keeping systems, which are now being planned, can be expected to easily overcome 5. Remark 4 will remain to some extent a problem, unless more sophisticated models that can capture this aspect are discovered.

6. Remark 6 is likely true, but perhaps unimportant.

7. Remark 7 is possible, but deemed unlikely.

8. Remark 8 is likely, but perhaps unimportant.

To sum up, the more serious errors are the couplings of Type 1 and 2, and the parameter estimation problem stemming from incomplete knowledge of the true shutting-off relationships. Overall, the formula $A_{..}$ predicts fairly closely. This will be our model on which our recommendations are based.

3.3 Some Specific Recommendations for Improvement

Before presenting tables, we have the following points to make.

1. For Mode 1, subsystems 1, 8, and 3, (in descending order of importance) are most responsible for the current low level of $A_{..}$, .698. (Subtracting .05 to give the actual system availability, .648; it is believed that an increase in the value given by the formula of $A_{..}$ would result in about the same amount of increase in the actual A.) This is obvious from how the number .698 is arrived at (repeated here for clarity):

$$\overset{①}{.815} \times \overset{③}{.965} \times .986 \times 1.000 \times .989 \times .995 \times \overset{⑧}{.933}$$
$$\times .984 \times .999 \times 1 \times .998 \times .998 = .698 .$$

Notice

$$.815 = .815$$
$$.815 \times .933 = .760$$
$$.815 \times .933 \times .965 = .734 .$$

Thus, it would be fruitless to improve the others now unless it is disproportionately cheap to do so. More formally, the following expressions are self-explanatory.

$$\left.\frac{\dfrac{\partial A_{\cdot\cdot}}{\partial \hat{\mu}_1}}{\dfrac{\partial A_{\cdot\cdot}}{\partial \hat{\mu}_3}}\right|_0 = \left.\frac{\dfrac{1}{1 + \dfrac{\hat{\nu}_1}{\hat{\mu}_1}} \cdot \dfrac{\hat{1}}{\hat{\mu}_1} \cdot \dfrac{1}{\hat{\mu}_1}}{\dfrac{1}{1 + \dfrac{\hat{\nu}_3}{\hat{\mu}_3}} \cdot \dfrac{\hat{\nu}_3}{\hat{\mu}_3} \cdot \dfrac{1}{\hat{\mu}_3}}\right|_0 = 48.87 \ ,$$

$$\left.\frac{-\dfrac{\partial A_{\cdot\cdot}}{\partial \hat{\nu}_1}}{-\dfrac{\partial A_{\cdot\cdot}}{\partial \hat{\nu}_3}}\right|_0 = \left.\frac{\hat{\mu}_3 + \hat{\nu}_3}{\hat{\mu}_1 + \hat{\nu}_1}\right|_0 = 1.78 \ .$$

Among the three villains 1, 8, and 3, if improvements are restricted to MTBF's, then *initially* 1 is about 50 times as important as 3. If improvements are restricted to MTTR's, then initially 1 is about twice as important as 3.

2. Improving the Adam injector, assuming no coupling of Type 2, will improve the availability of Mode 1 *only*, while improving the other subsystems 3-12 and 14 will increase the availability of Mode 2 as well, due to the coupling of Type 1.

3. Likewise, for Mode 2, the top three culprits are subsystems 8, 2, and 3.

4. Notice both 8 and 3 are mentioned twice. They are definitely worthy of improvement. Subsystem 8 is "others." This underlines the need for further refining this category. [See Section 3.5 of this chapter.] 3 is radio frequency; as mentioned before, both modes would benefit from its improvement.

TABLE 4

MODE 1

IMPROVEMENT BY VARYING SUBSYSTEM 1

MTBF ↑ by $\hat{\mu}_1$ (Current Value = 22.74 hrs. MTTR Held Fixed)		MTTR ↓ by $\hat{\nu}_1$ (Current Value = 5.15 hrs. MTBF Held Fixed)	
	Percentage Increase in A_1	Percentage Increase in A_1	
5 hrs.	2.4%	1.3%	.5 hrs.
10	4.2	2.6	1.0
15	5.6	4.0	1.5
20	6.6	5.4	2.0
25	7.5	6.9	2.5
30	8.2	8.5	3.0
35	8.8	10.1	3.5
40	9.4	11.7	4.0
45	9.8	13.5	4.5
50	10.2	15.3	5.0
100	12.4	15.8	5.15

It is believed that an increase in the value given by the formula of $A_{..}$ would result in about the same amount of increase in actual A. We caution that the improvement in A_1 is less than additive when varying the MTBF and MTTR simultaneously in the same subsystem. However, the result is more than additive if we improve 2 or more subsystems at the same time.

For other tables of this sort, see Appendix 2.

3.4 An Optimization Example

Example:

Consider the Adam injector of Mode 1. Suppose that it is desired to vary the $\hat{\mu}_1$ and $\hat{\nu}_1$ simultaneously from their current value of 22.74 hrs. and 5.15 hrs. so that the overall increase in A_1 is 10%. Assume that all other parameters are held fixed. Suppose further that it costs 2 units of money for 1 hr. of increase in $\hat{\mu}_1$ and 1 unit of money for 1 hr. of decrease in $\hat{\nu}_1$. Also, from the viewpoint of the state of the art, time, budget, etc., it is considered impractical to boost the MTBF beyond 32.74 hrs. or to reduce the MTTR below 2 hours. Does a solution exist for the desired 10% increase in A_1? If yes, what is it?

Solution:

Let x be the number of hours we should increase MTBF. Let y be the number of hours we should decrease MTTR. Then

$$\left(\frac{1}{1+\frac{5.15-y}{22.74+x}}\right)(.698) \div \left(\frac{1}{1+\frac{5.15}{22.74}}\right) - .698 = .1 \ ,$$

i.e., $0.073x + y = 3.49$.

So the problem is to

$$\text{Minimize} \qquad 2x + y$$

$$\text{subject to} \begin{cases} 0.073x + y = 3.49 \ , \\ 10 \geq x \geq 0 \ , \\ 3.15 \geq y \geq 0 \ , \end{cases}$$

where $2x + y$ is the cost incurred.

This is a linear programming problem, but since it will in general become nonlinear when 2 or more subsystems are considered, or when the costs are nonlinear, we will solve it in that setting. By the method of p. 233-234 [18] (similar to the idea of Lagrange multipliers), we get

$$y = 3.15 \text{ hrs.}$$

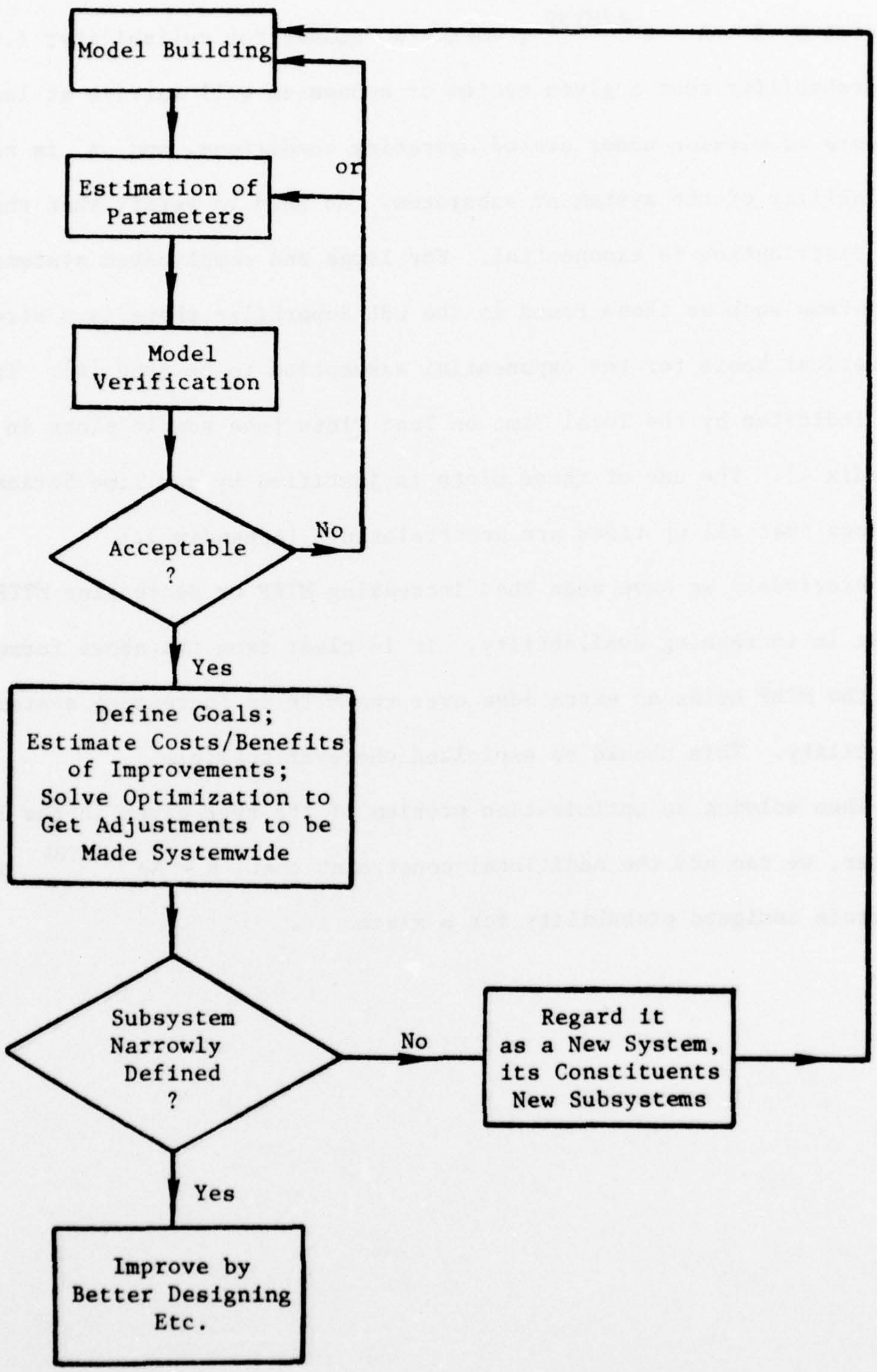
$$x = 4.66 \text{ hrs.}$$

The cost = 2(4.66) + 1(3.15) = 12.47 units.

In general we will need a computer to solve realistic problems. Standard algorithms for such nonlinear programming problems exist, as we have indicated in the above formulation.

3.5 An Iterative Diagram

The diagram is self-explanatory.



CHAPTER 4

SYSTEM RELIABILITY

We briefly justify the use of the exponential function in the expression $R = A \cdot e^{-t/MTBF}$, where R stands for reliability; i.e., the probability that a given system or subsystem will survive at least t hours of mission under stated operating conditions, and A is the availability of the system or subsystem. We need to verify that the up time distribution is exponential. For large and complicated systems or subsystems such as those found in the LBL Superhilac there is a strong theoretical basis for the exponential assumption to be true [4]. This is also indicated by the Total Time on Test Plots [see sample plots in Appendix 4]. The use of these plots is justified by our Time Series Analysis findings that all up times are uncorrelated. [Appendix 3.]

Previously we have seen that increasing MTBF or decreasing MTTR will result in increasing availability. It is clear from the above formula that the MTBF holds an extra edge over the MTTR in increasing system reliability. This should be exploited wherever possible.

When solving an optimization problem of the type given in the last chapter, we can add the additional constraint that $R = Ae^{-t/MTBF}$ be $\geq$ a certain assigned probability for a given t.

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APPENDIX 1

The exact shutting-off relationships between subsystems of the Superhilac are not known. The relationships also change with time as more monitoring and controlling computers are wired to various parts of the accelerator. Hence, the following chart represents only a partial description of what really happens.

Subsystem	Other Subsystems Shut Off
1	None
2	None
3	None
4	None
5	None
6	None
7	None
8	None
9	4, 10, 11, and 12
10	4
11	4
12	4, 9, and 11
13	None
14	1-13

The up times of subsystems are calculated with the above chart in mind so as to estimate the subsystem parameters as accurately as possible. For example:

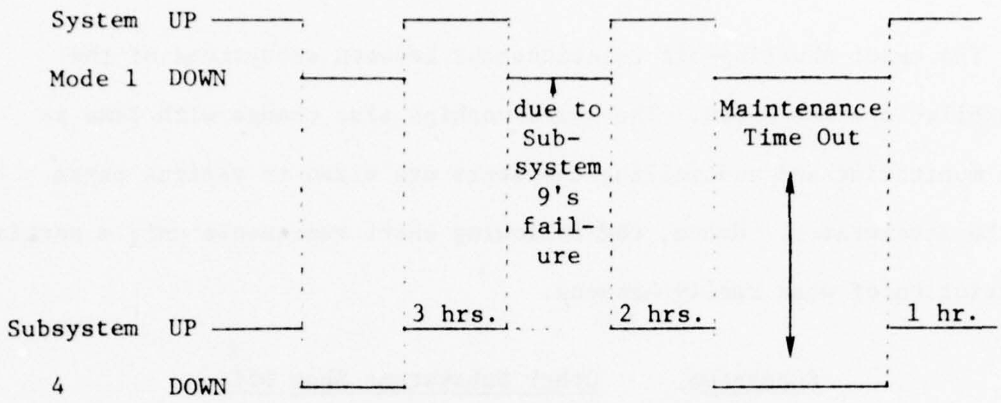


FIGURE 2

In the above Up Time and Down Time Histories, the 3 pieces of up time labeled 3 hrs., 2 hrs., and 1 hr. of subsystem 4 are lumped together as a single up time of 6 hrs. in the calculation of the MTBF.

APPENDIX 2

TABLE 1

MODE 1

IMPROVEMENT BY VARYING SUBSYSTEM 3

MTBF ↑ by $\hat{\mu}_3$ (Current Value = 47.90 hrs. MTTR $\hat{\nu}_3$ Held Fixed)	Percentage Increase in A_1	Percentage Increase in A_1	MTTR ↓ by $\hat{\nu}_3$ (Current Value = 1.76 hrs. MTBF Held Fixed)
5 hrs.	0.2%	0.7%	0.5 hrs.
10	0.4	1.4	1.0
15	0.6	2.1	1.5
20	0.7		

TABLE 2

MODE 1

IMPROVEMENT BY VARYING SUBSYSTEM 8

MTBF ↑ by $\hat{\mu}_8$ (Current Value = 18.70 hrs. MTTR Held Fixed)		MTTR ↓ by $\hat{\nu}_8$ (Current Value = 1.35 hrs. MTBF Held Fixed)	
	Percentage Increase in A_1	Percentage Increase in A_1	
5 hrs.	.98%	1.04%	0.3 hrs.
10	1.65	2.13	0.6
15	2.13	3.25	0.9
20	2.49	4.42	1.2
25	2.77	5.01	1.35
30	3.00		
100	4.17		

TABLE 3

MODE 2

IMPROVEMENT BY VARYING SUBSYSTEM 2

MTBF ↑ by $\hat{\mu}_2$ (Current Value = 24.7 hrs. MTTR Held Fixed)		MTTR ↓ by $\hat{\nu}_2$ (Current Value = 1.61 hrs. MTBF Held Fixed)	
	Percentage Increase in A_2	Percentage Increase in A_2	
5 hrs.	.72%	.81%	.3 hrs
10	1.32	1.75	.6
15	1.77	2.70	.9
20	2.13	3.68	1.2
30	2.65	4.68	1.5
50	3.28	5.06	1.61
100	3.98		

TABLE 4

MODE 2

IMPROVEMENT BY VARYING SUBSYSTEM 3

MTBF ↑ by $\hat{\mu}_3$ (Current Value = 55.5 hrs. MTTR Held Fixed)		MTTR ↓ by $\hat{\nu}_3$ (Current Value = 2.23 hrs. MTBF Held Fixed)	
	Percentage Increase in A_2	Percentage Increase in A_2	
5 hrs.	.37%	.81%	.5 hrs.
25	1.08	1.51	1.0
50	1.59	2.23	1.5
100	2.13	2.96	2.0
		3.30	2.23

APPENDIX 3

The main results from the Time Series Analysis are:

1. (i) No significant autocorrelations are found in up times and down times in any of the three systems (Mode 1, 2, and 3).

   (ii) No significant autocorrelations are found in up times and down times in any subsystems of Mode 2. (Only 2, 3, 4, 6, 7, 8, 9, and 13 are analyzed; the others do not have enough data points to provide a meaningful analysis.)

   (iii) No significant autocorrelations are found in up times of any subsystems of Mode 1. (Only 1, 3, 4, 6, 7, 8, 9, and 13 are analyzed.)

   (iv) No significant autocorrelations are found in the down times of any subsystems of Mode 1 *except* subsystem 13 (experimenter), the serial correlation of which is given by $Z_t = 0.22Z_{t-1} + 0.78Z_{t-2} + a_t$.

The above results imply that the use of Total Time on Test Plots to analyze the distributions of up times and down times is practically justified in all cases but one. It also means in particular that any two consecutive up times are well-shielded from each other by the intervening repair work and possibly also by regular maintenance work.

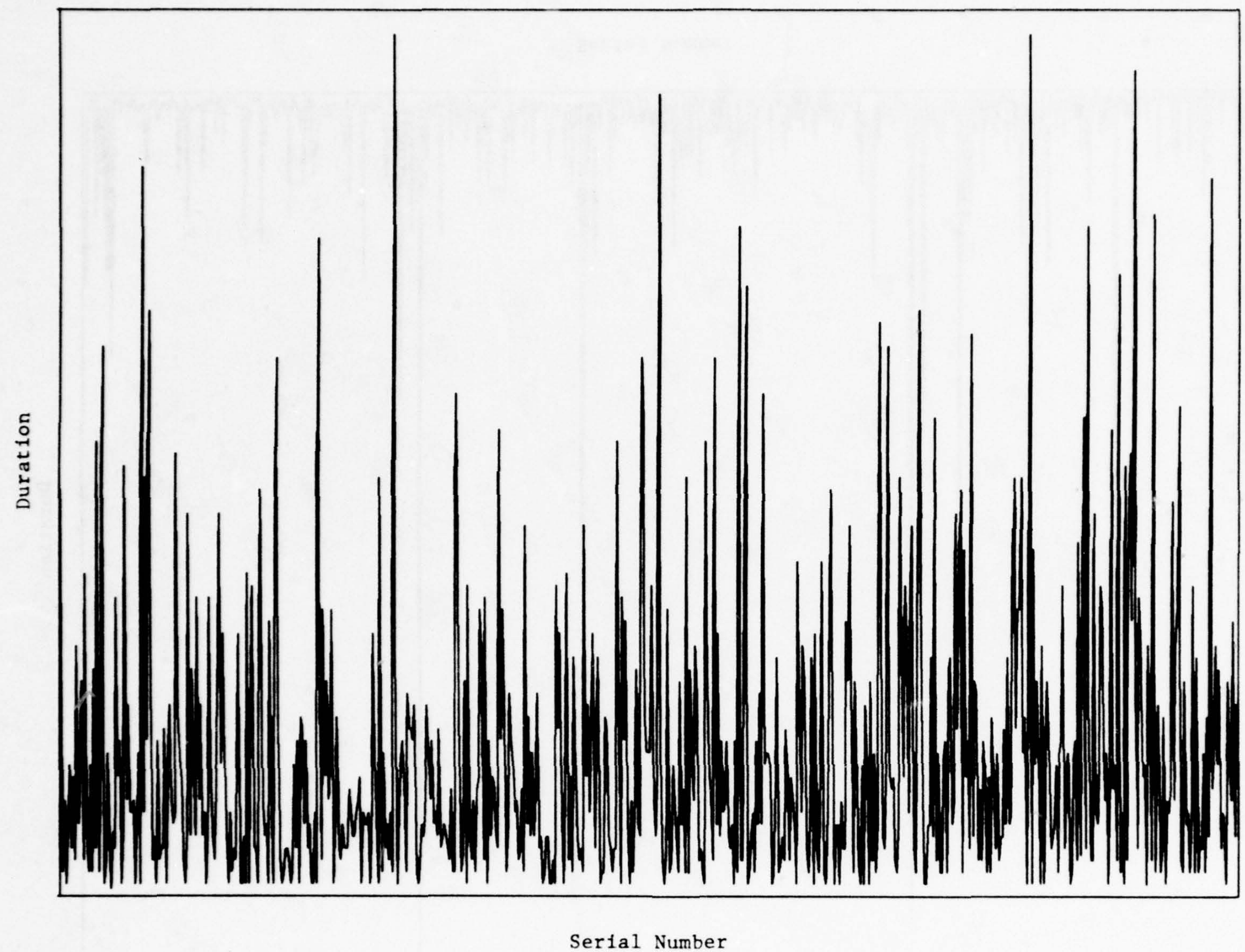
2. No cross correlations are found between any pair of up time and down time sequences, i.e., for all three modes and for all subsystems of both Mode 1 and Mode 2.

   This has, in particular, partially verified the requirement that all random variables in our models be independent of each other.

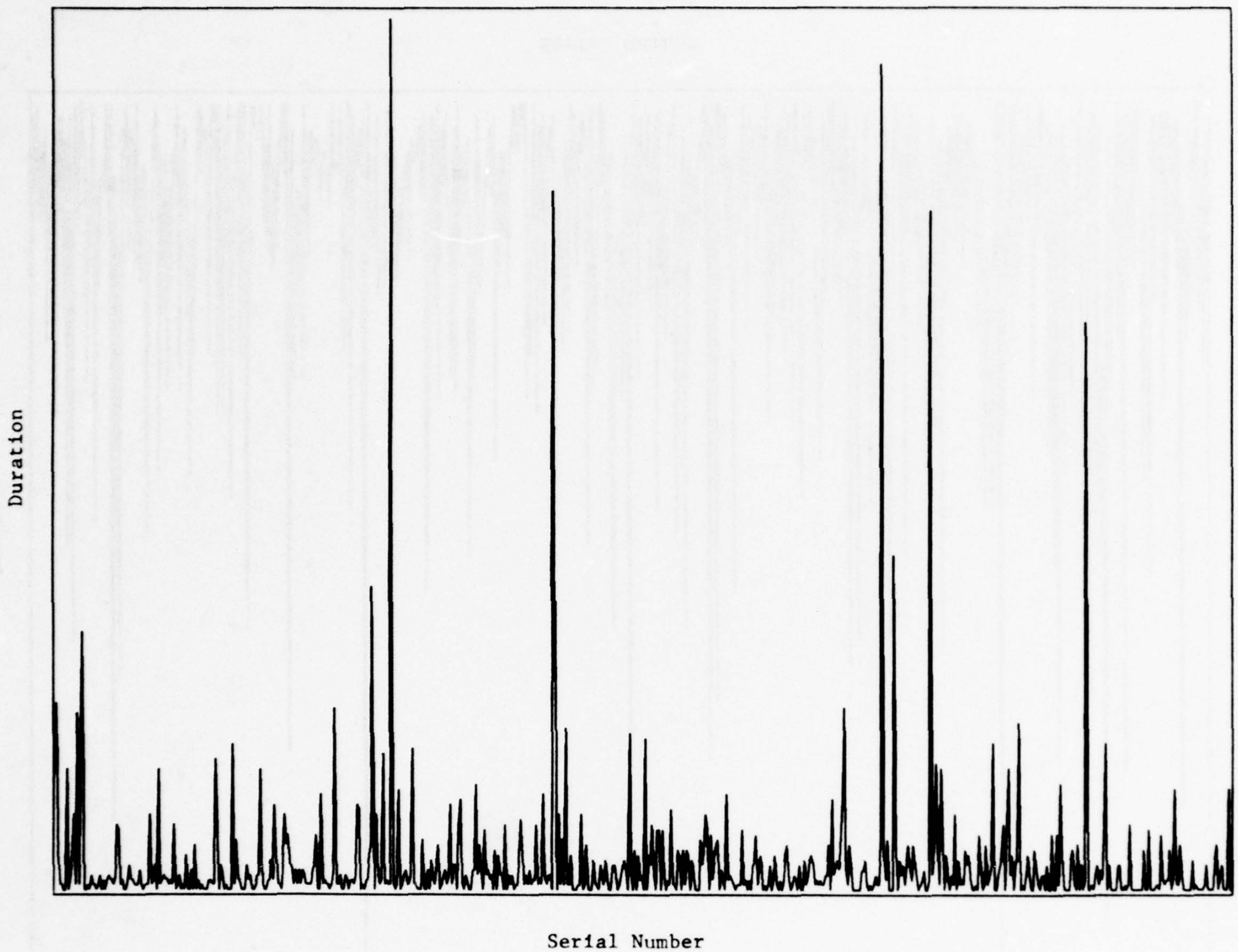
   This also confirms that each repair is fairly complete so that one cannot link in any manner the immediately following up time to it [23].

3. The panoramic graphs of the up time and down time sequences of Mode 1, 2, and 3 for the entire period of 26 months are attached here for easy comparison.

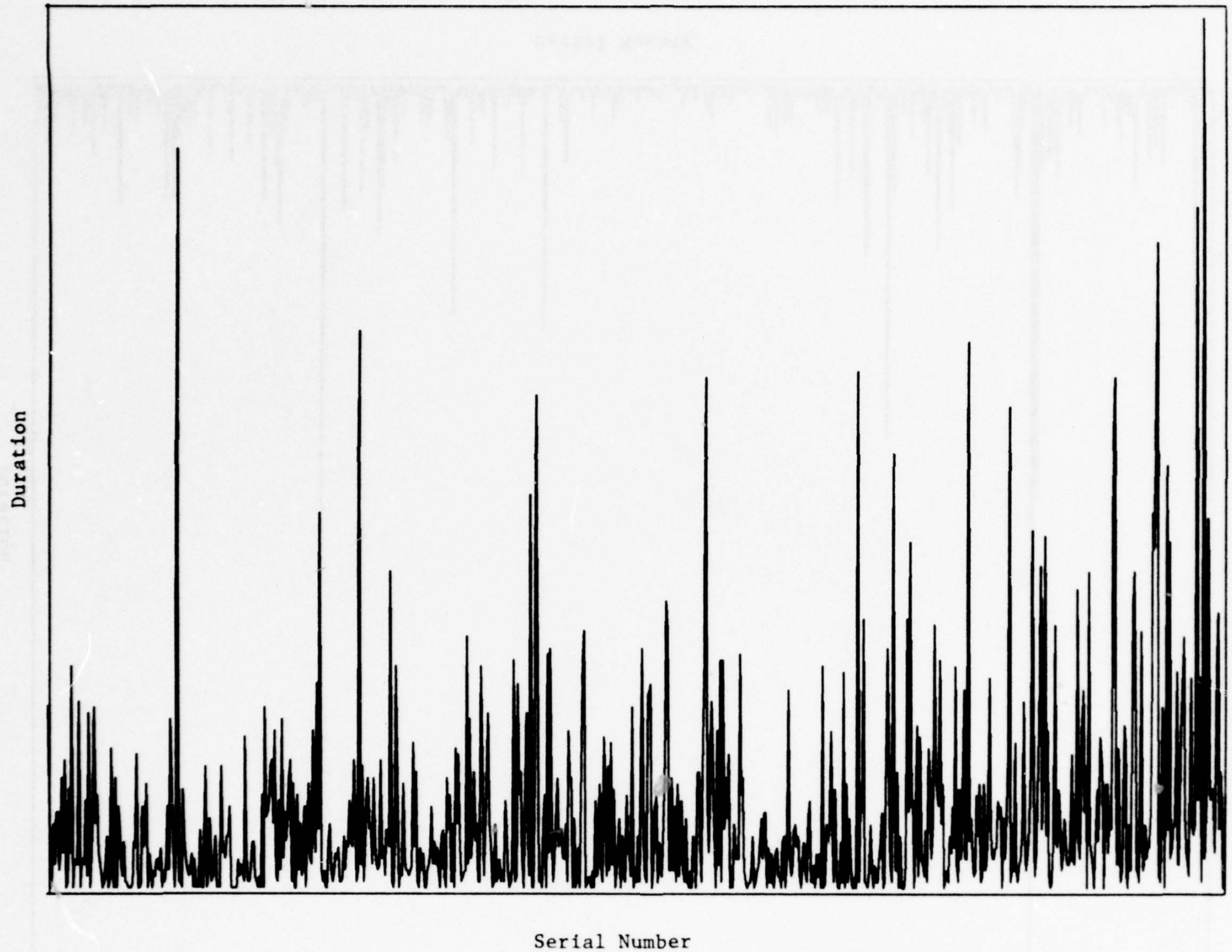
The time series analysis was made using the computer codes described in [24].



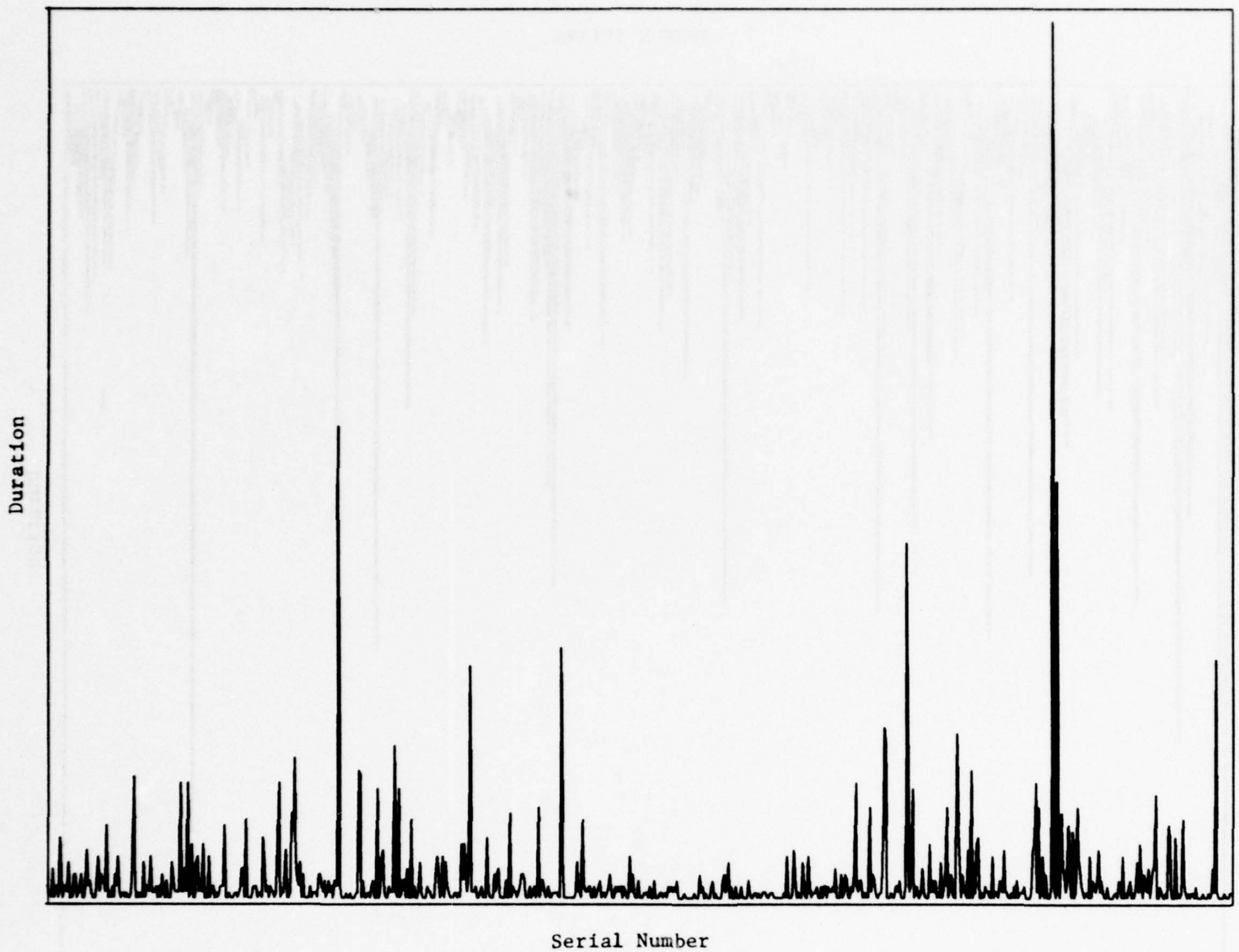
System Uptimes for Mode 1



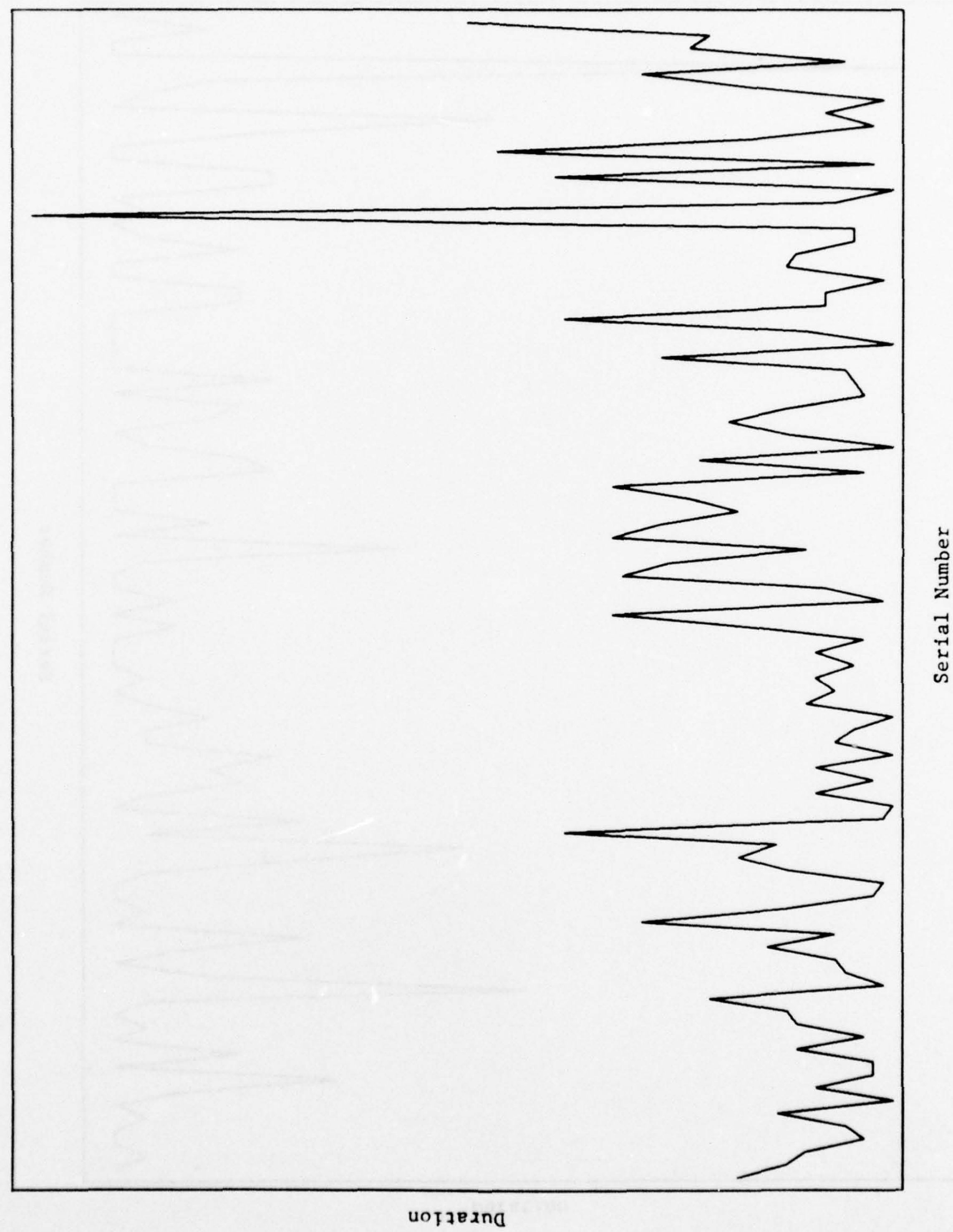
System Downtimes for Mode 1



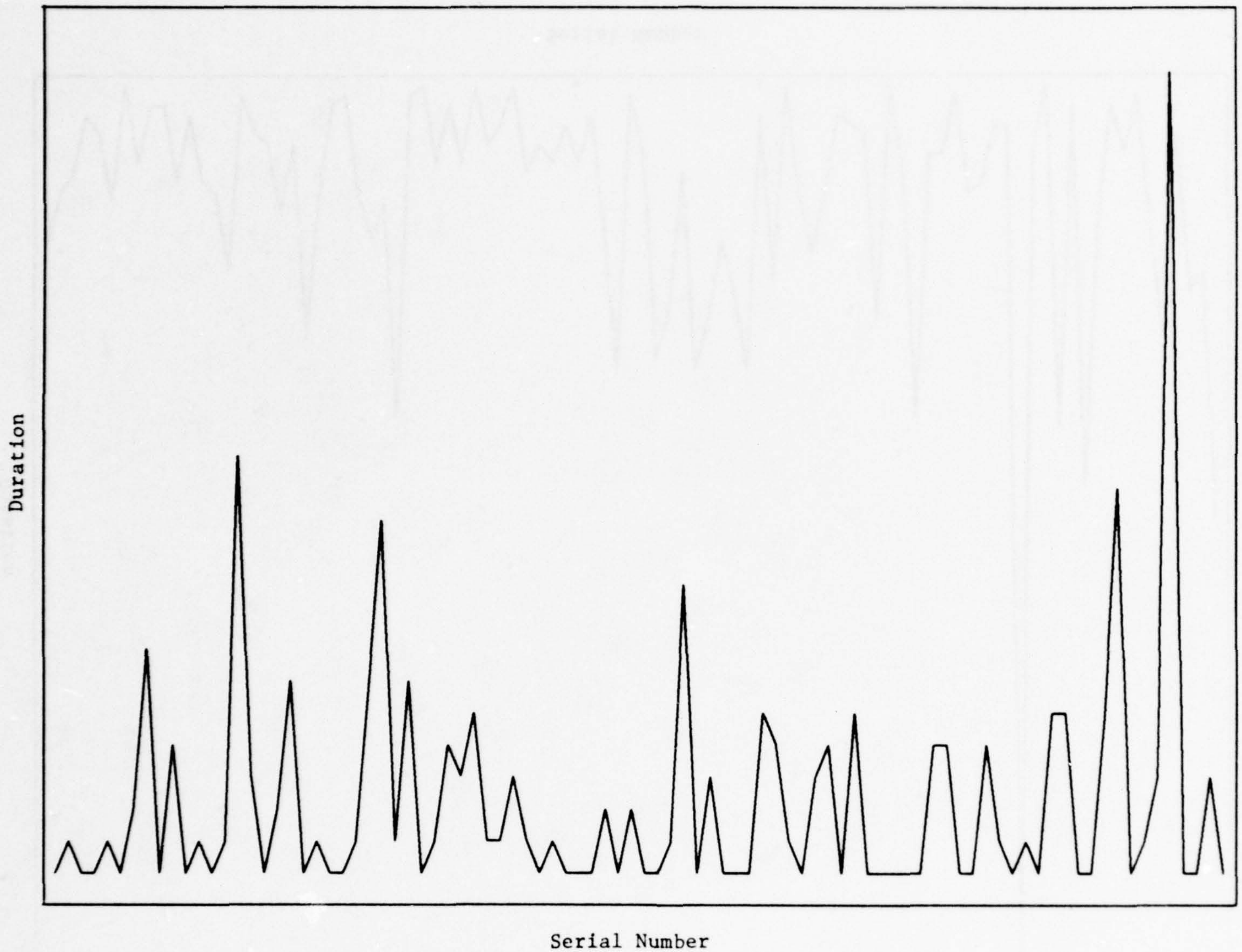
System Uptimes for Mode 2



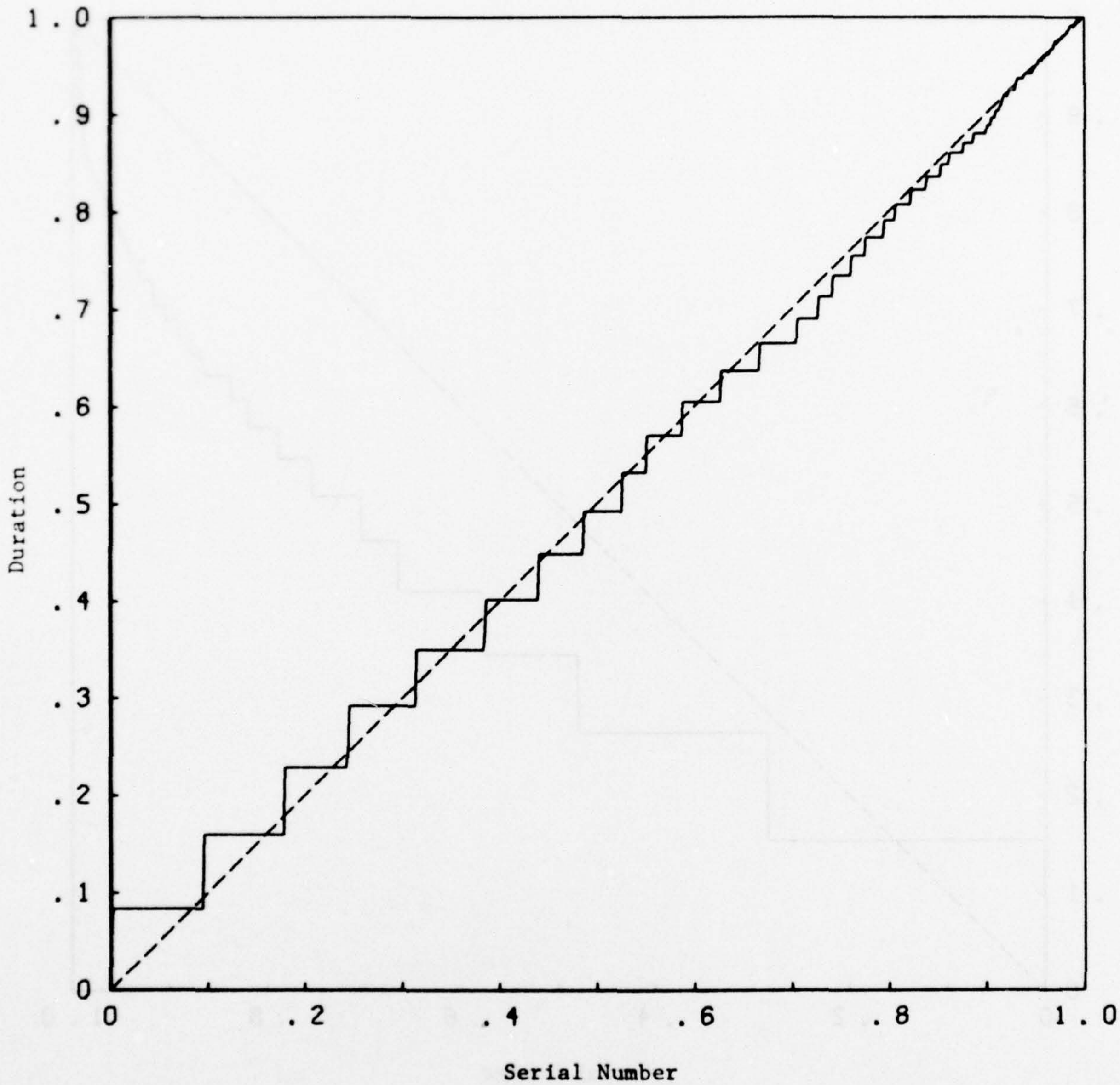
System Downtimes for Mode 2



System Uptimes for Mode 3

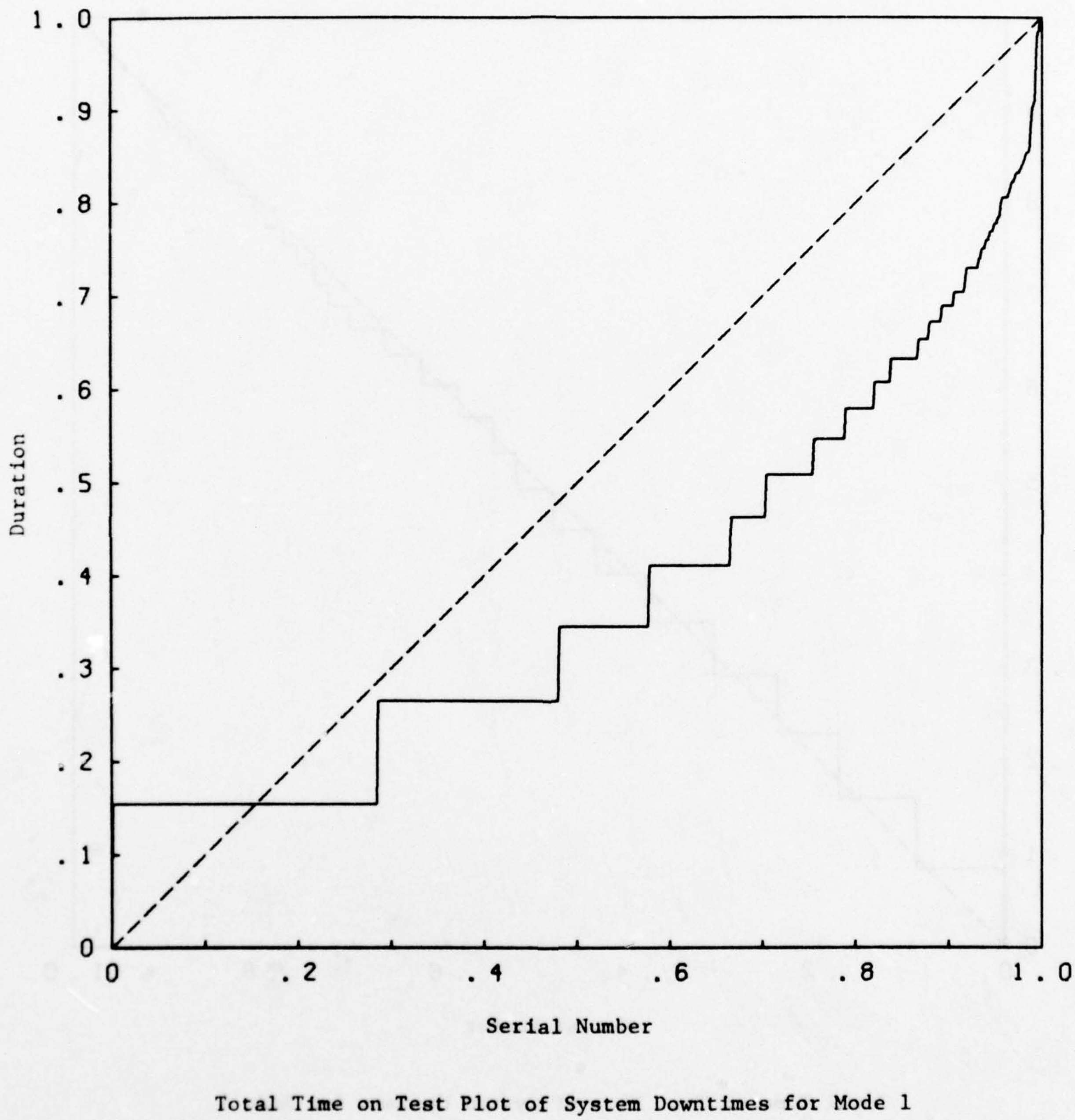


System Downtimes for Mode 3



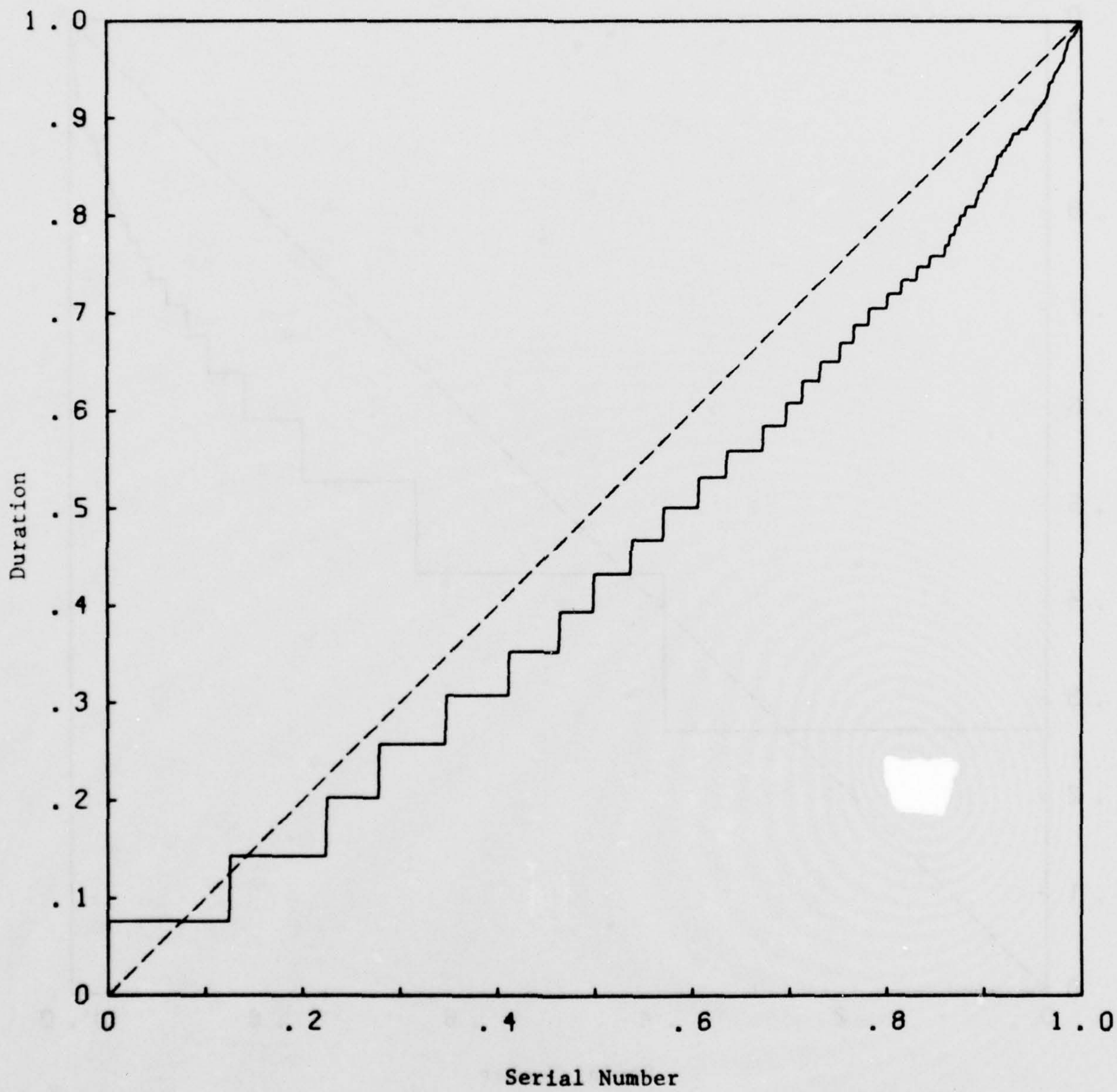
Total Time on Test Plot of System Uptimes for Mode 1

Coefficient of Variation = 1.00934



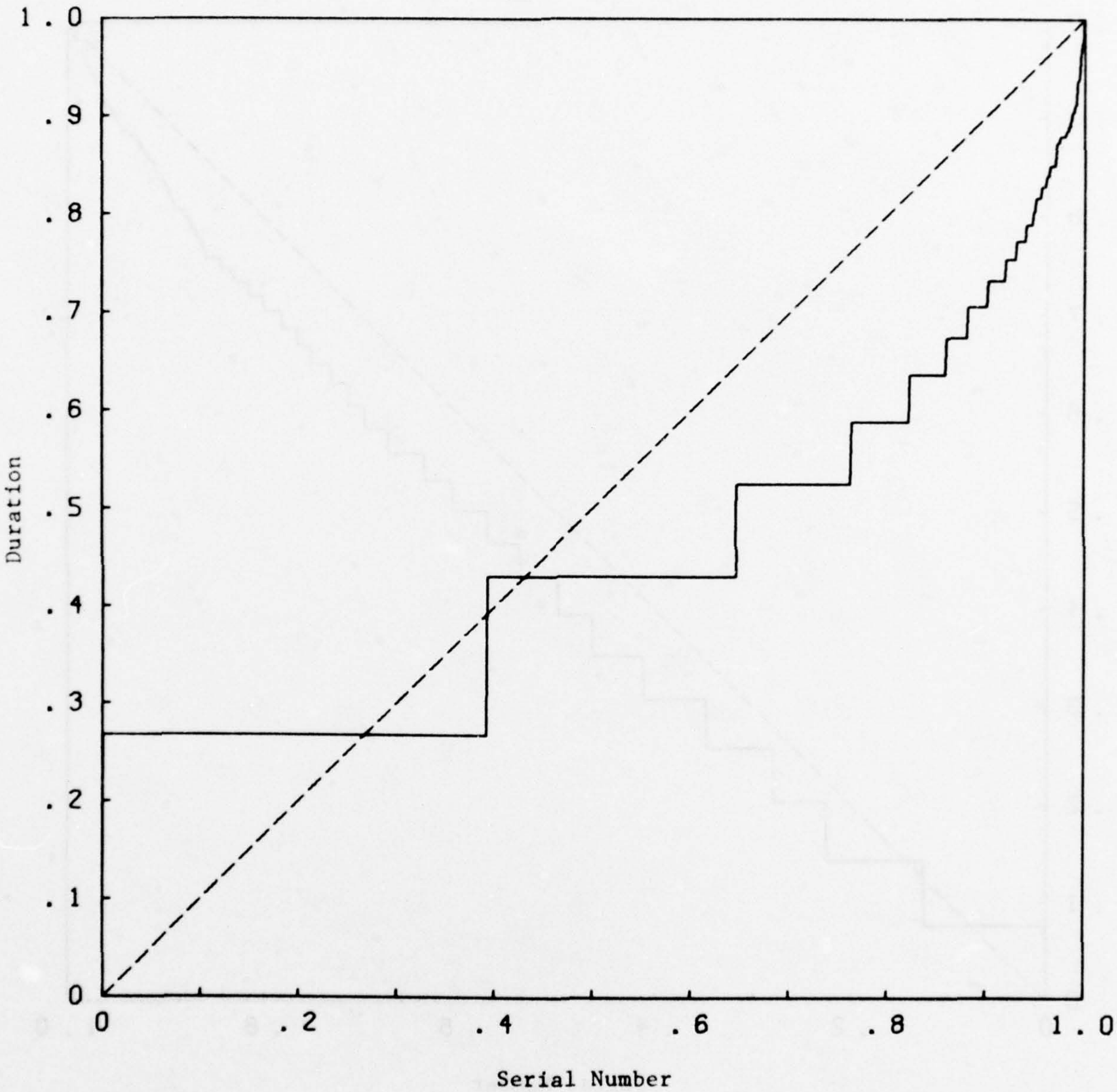
Total Time on Test Plot of System Downtimes for Mode 1

Coefficient of Variation = 2.20113



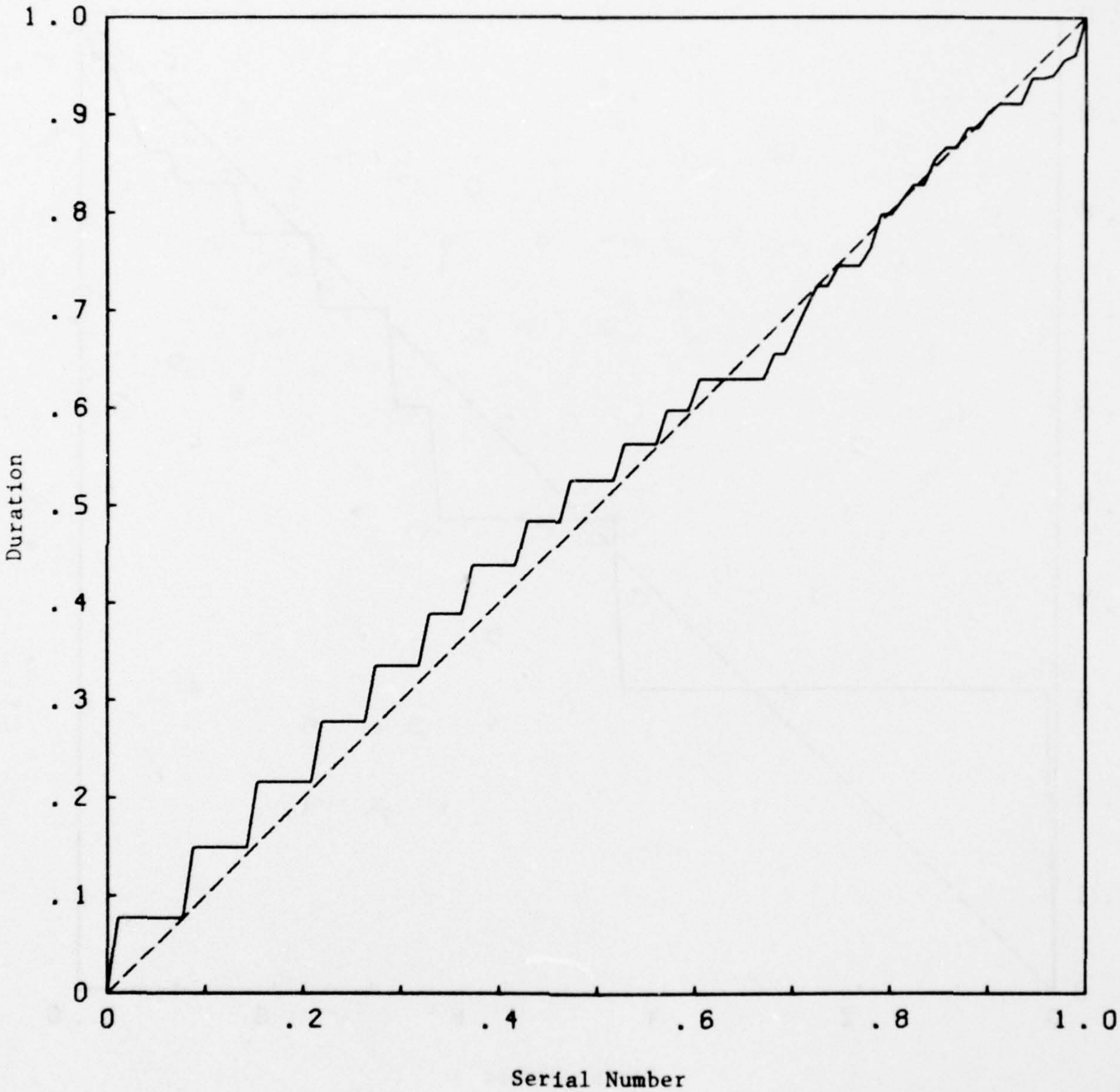
Total Time on Test Plot of System Uptimes for Mode 2

Coefficient of Variation = 1.28049



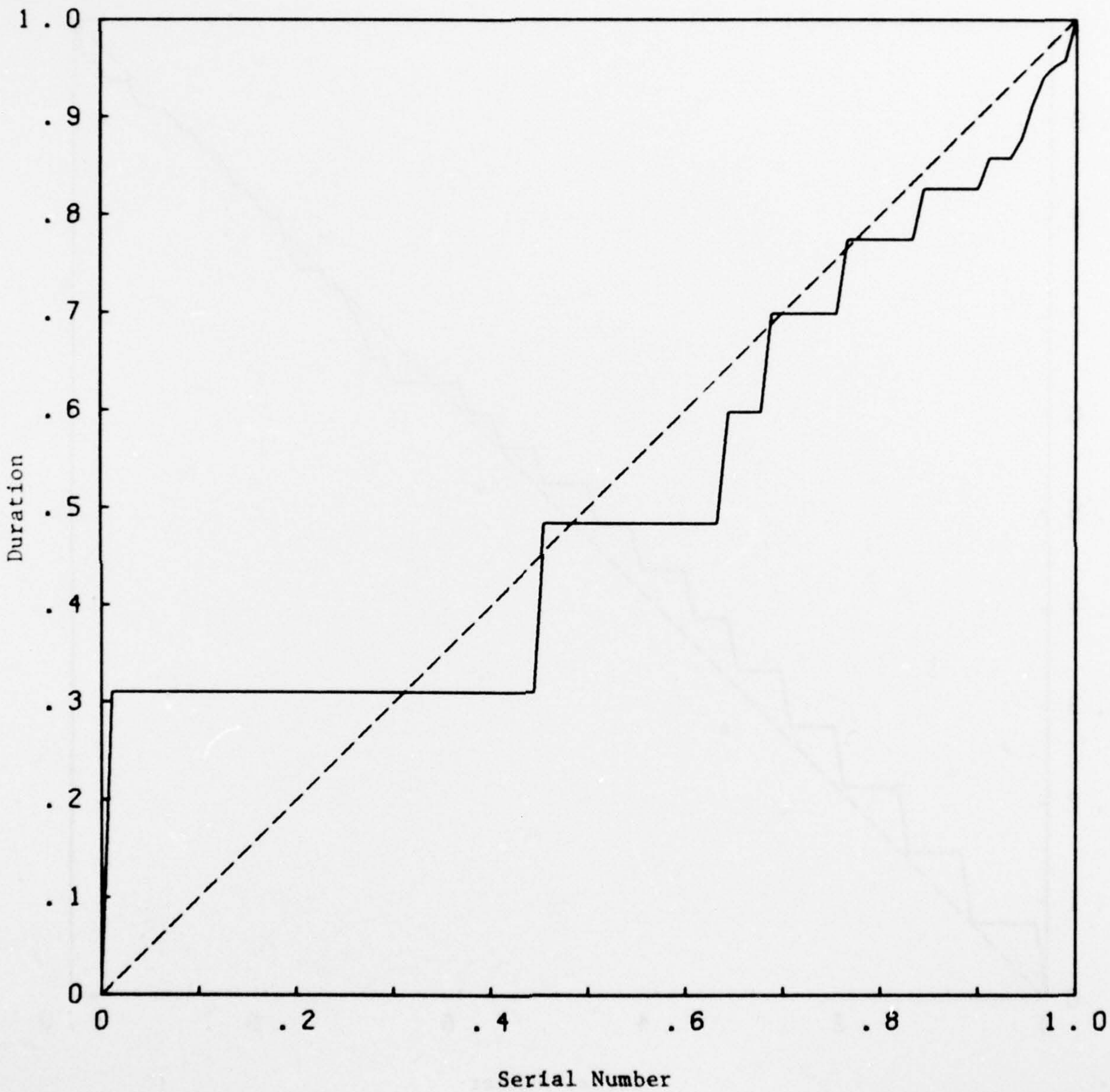
Total Time on Test Plot of System Downtimes for Mode 2

Coefficient of Variation = 2.06686



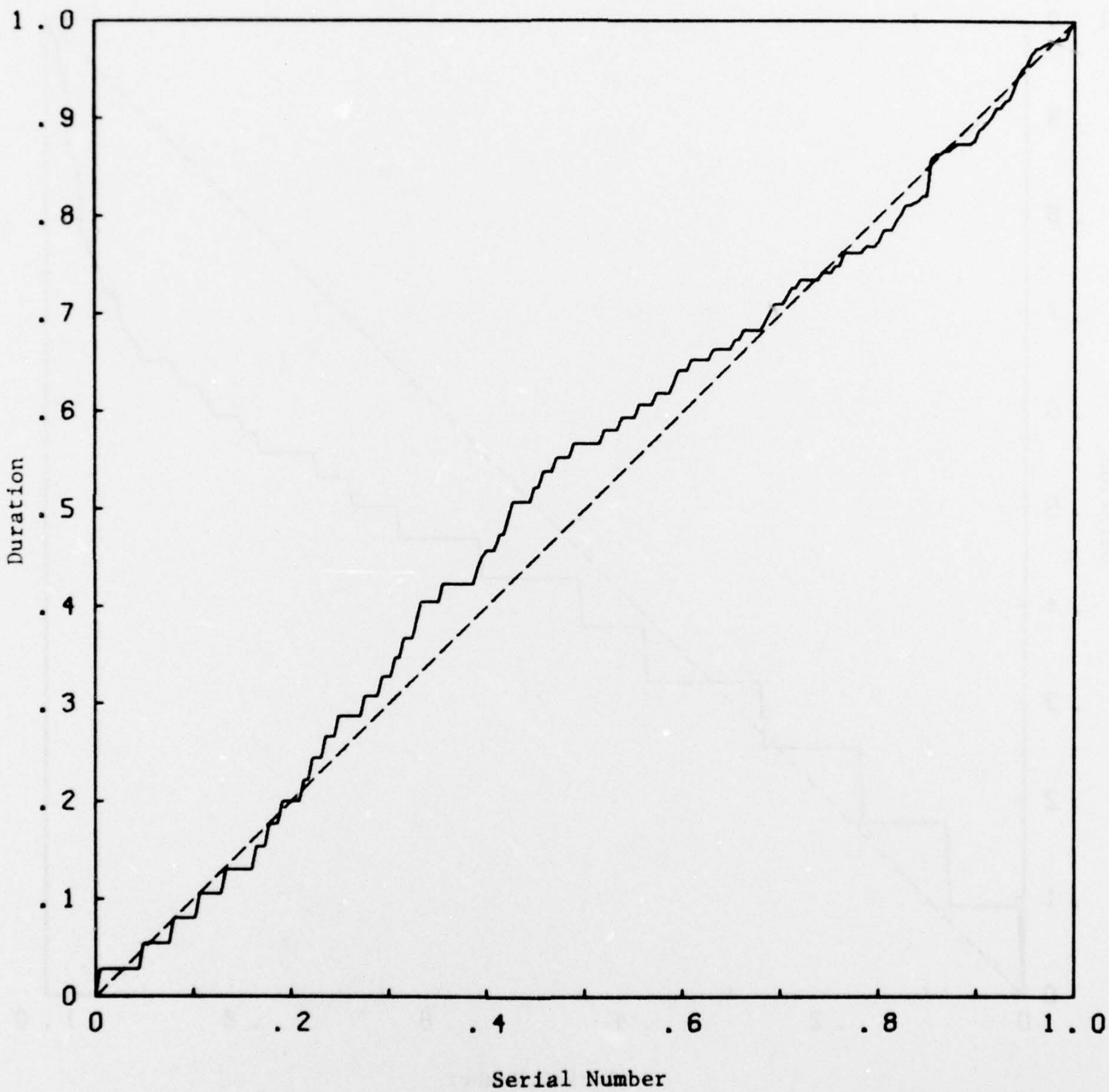
Total Time on Test Plot of System Uptimes for Mode 3

Coefficient of Variation = 1.01203



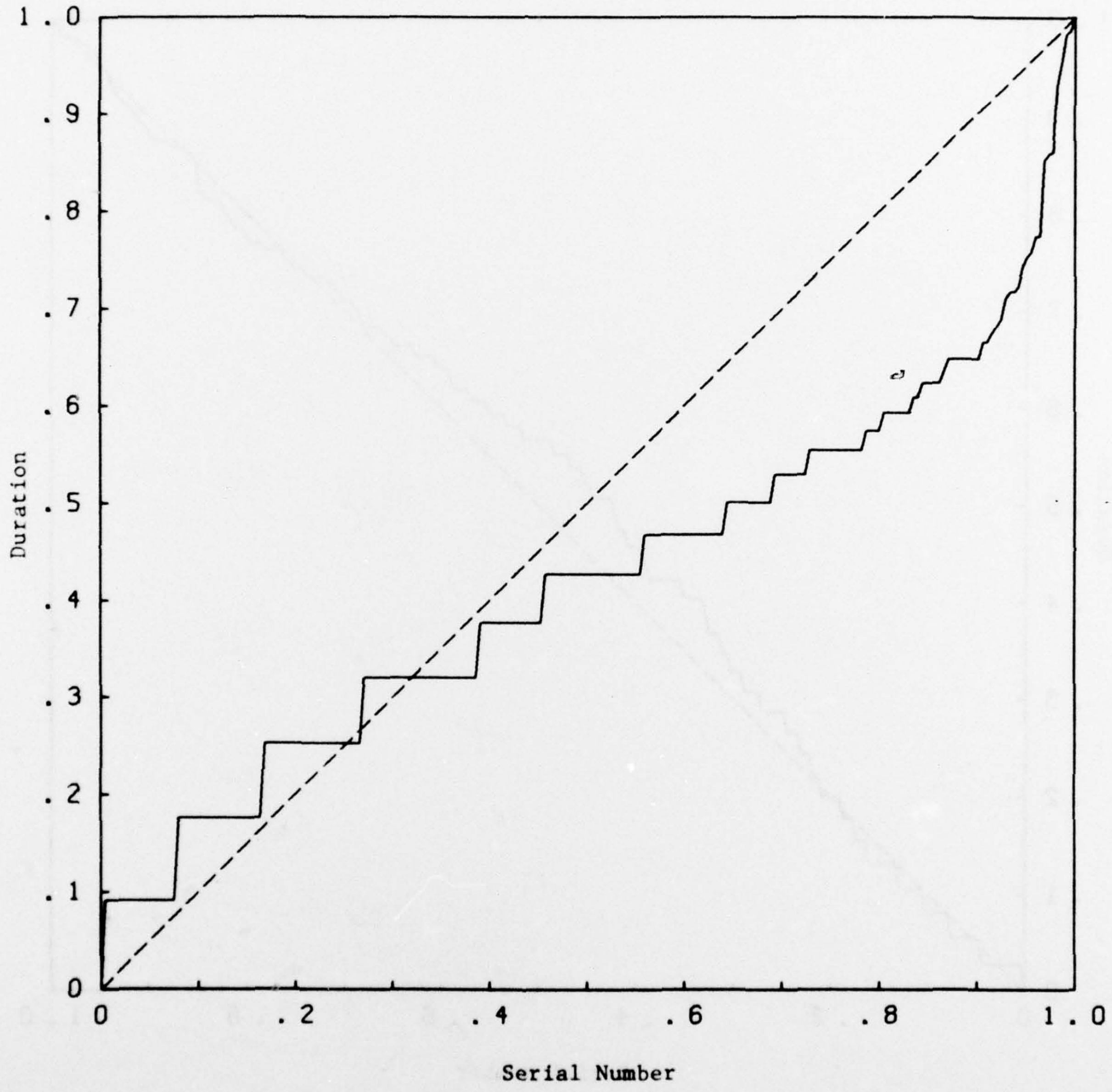
Total Time on Test Plot of System Downtimes for Mode 3

Coefficient of Variation = 1.14422



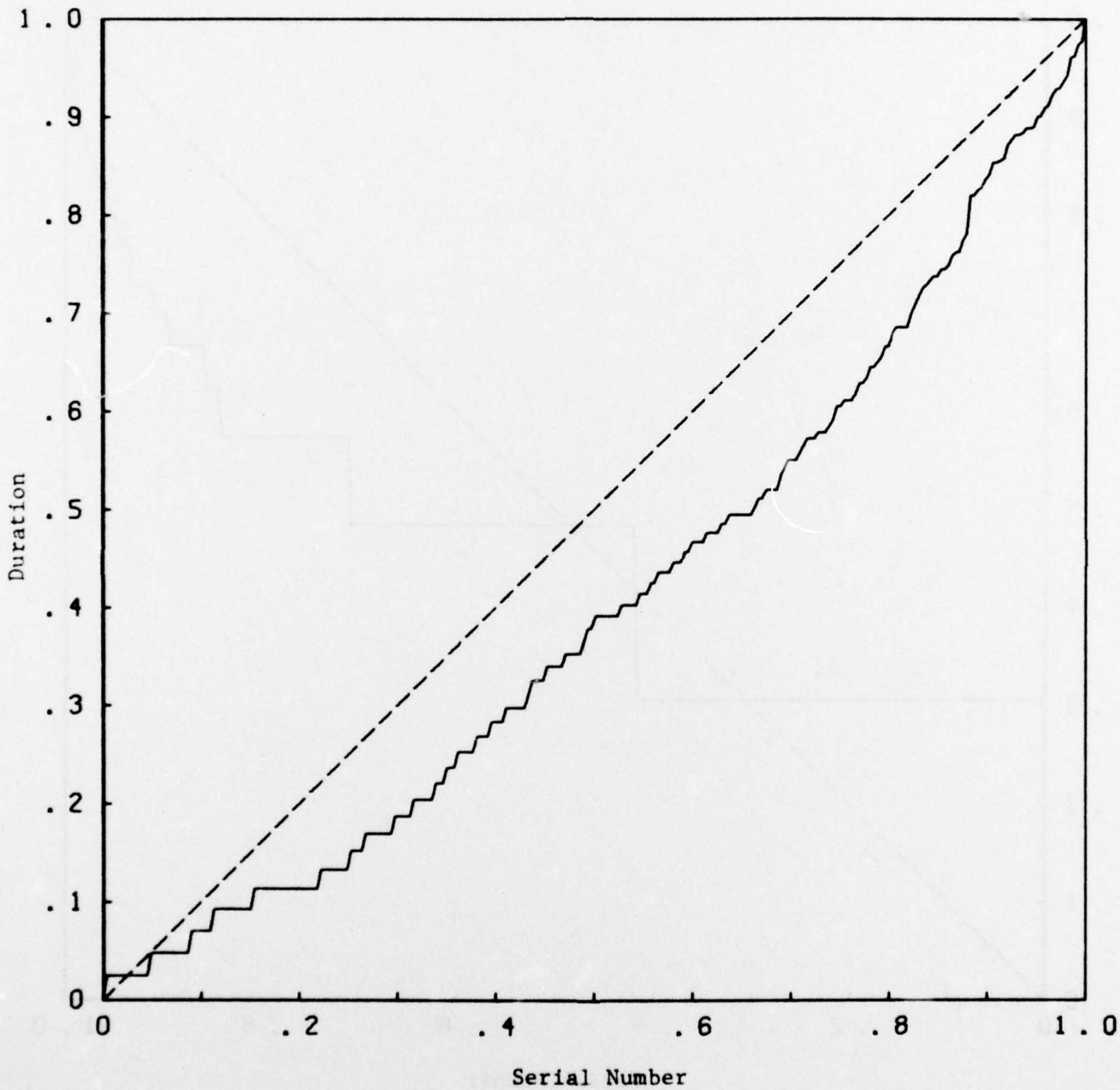
Total Time on Test Plot of Uptimes of Subsystem 1 for Mode 1

Coefficient of Variation = 0.96912



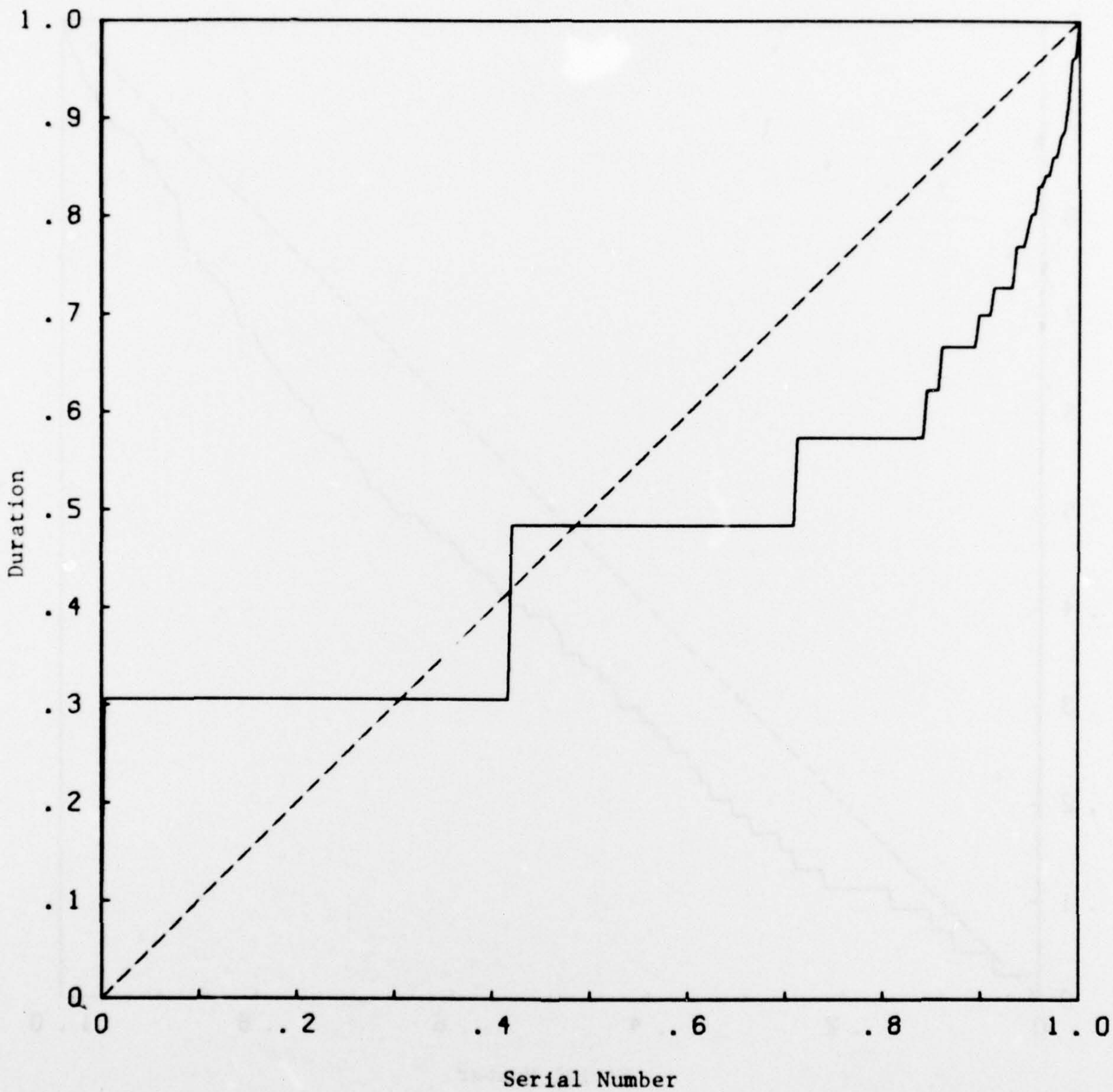
Total Time on Test of Downtimes of Subsystem 1 for Mode 1

Coefficient of Variation = 1.89563



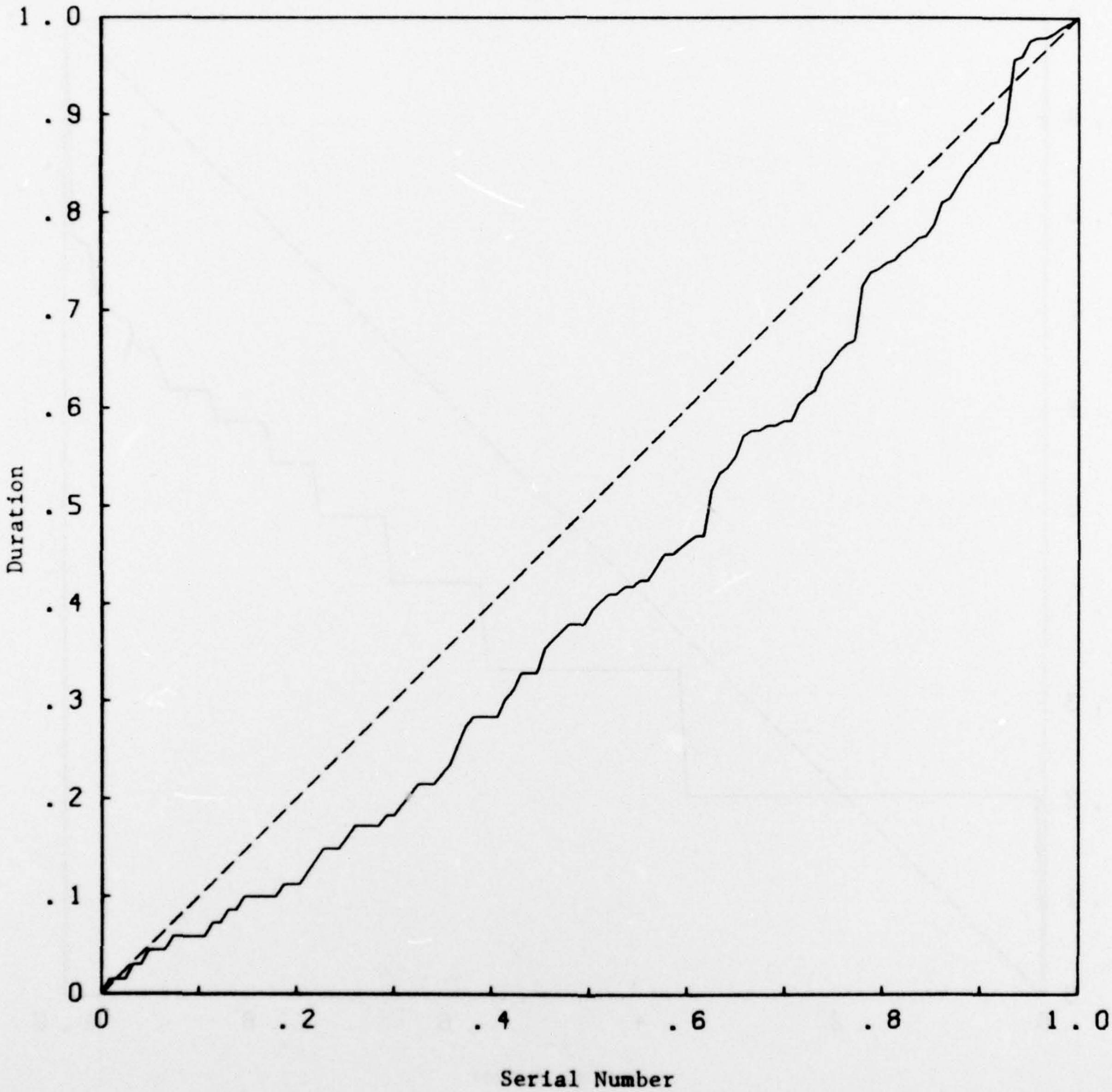
Total Time on Test of Uptimes of Subsystem 2 for Mode 2

Coefficient of Variation = 1.41121



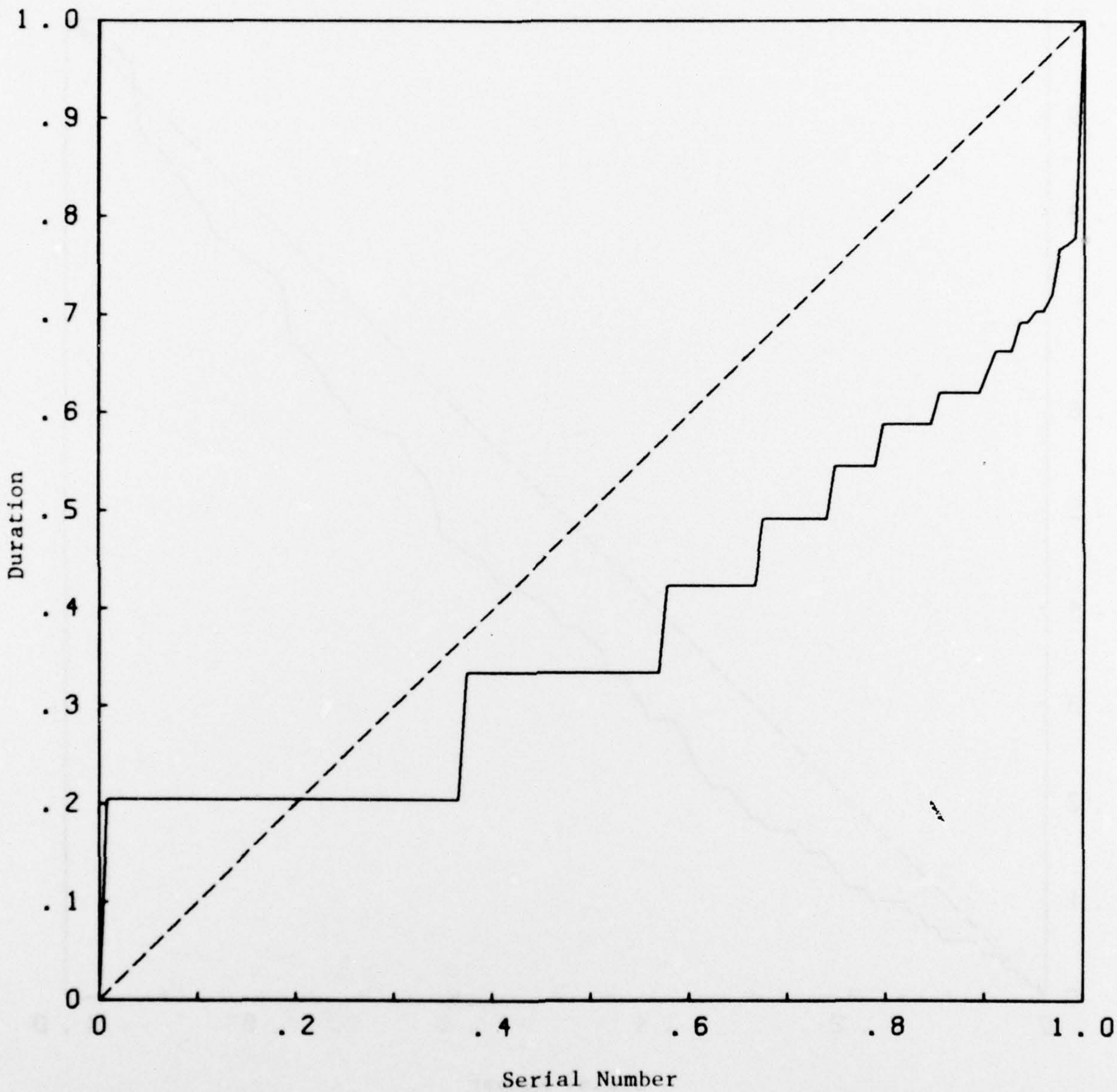
Total Time on Test Plot of Downtimes of Subsystem 2 for Mode 2

Coefficient of Variation = 1.89681



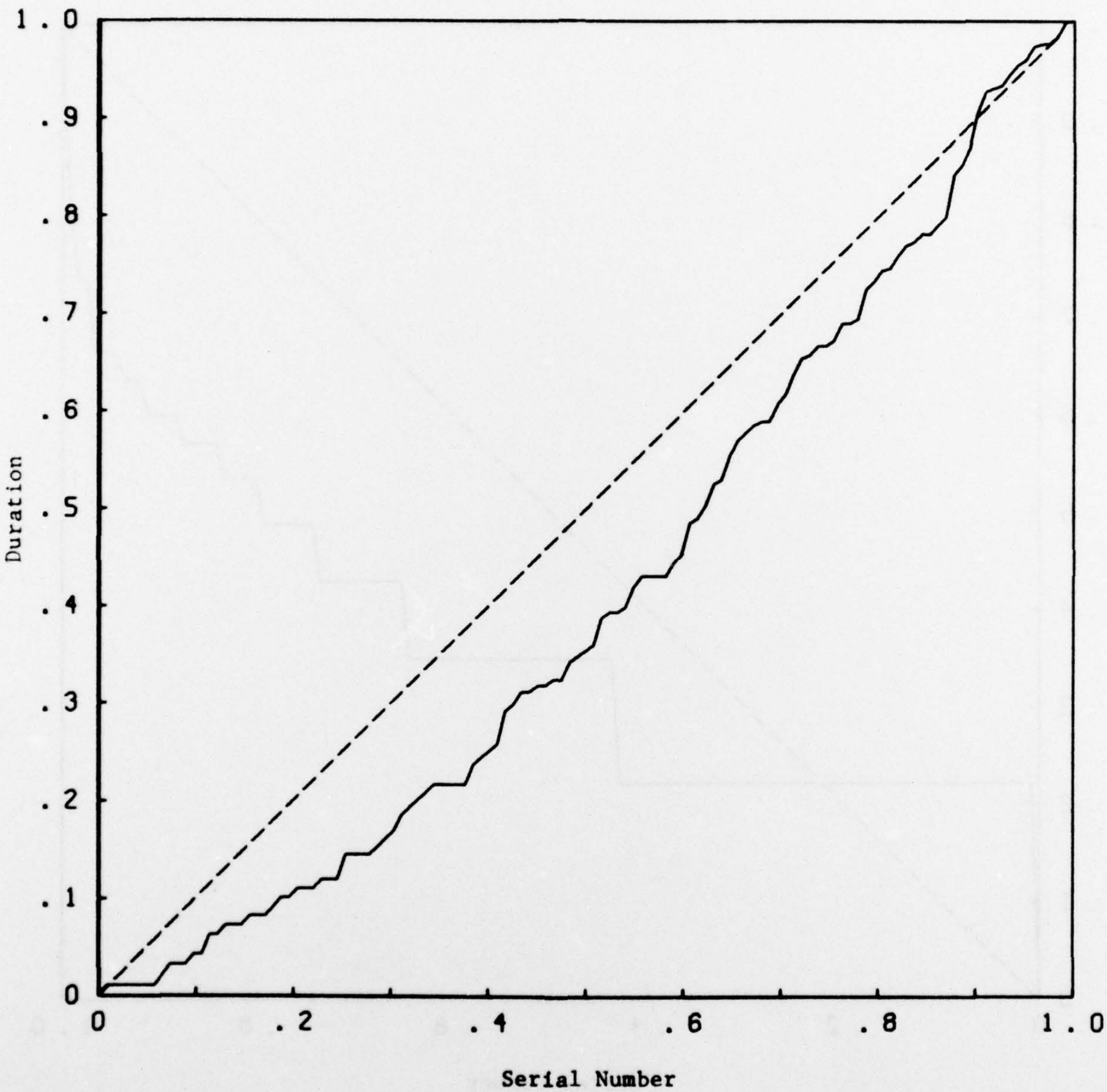
Total Time on Test of Uptimes of Subsystem 3 for Mode 1

Coefficient of Variation = 1.17688



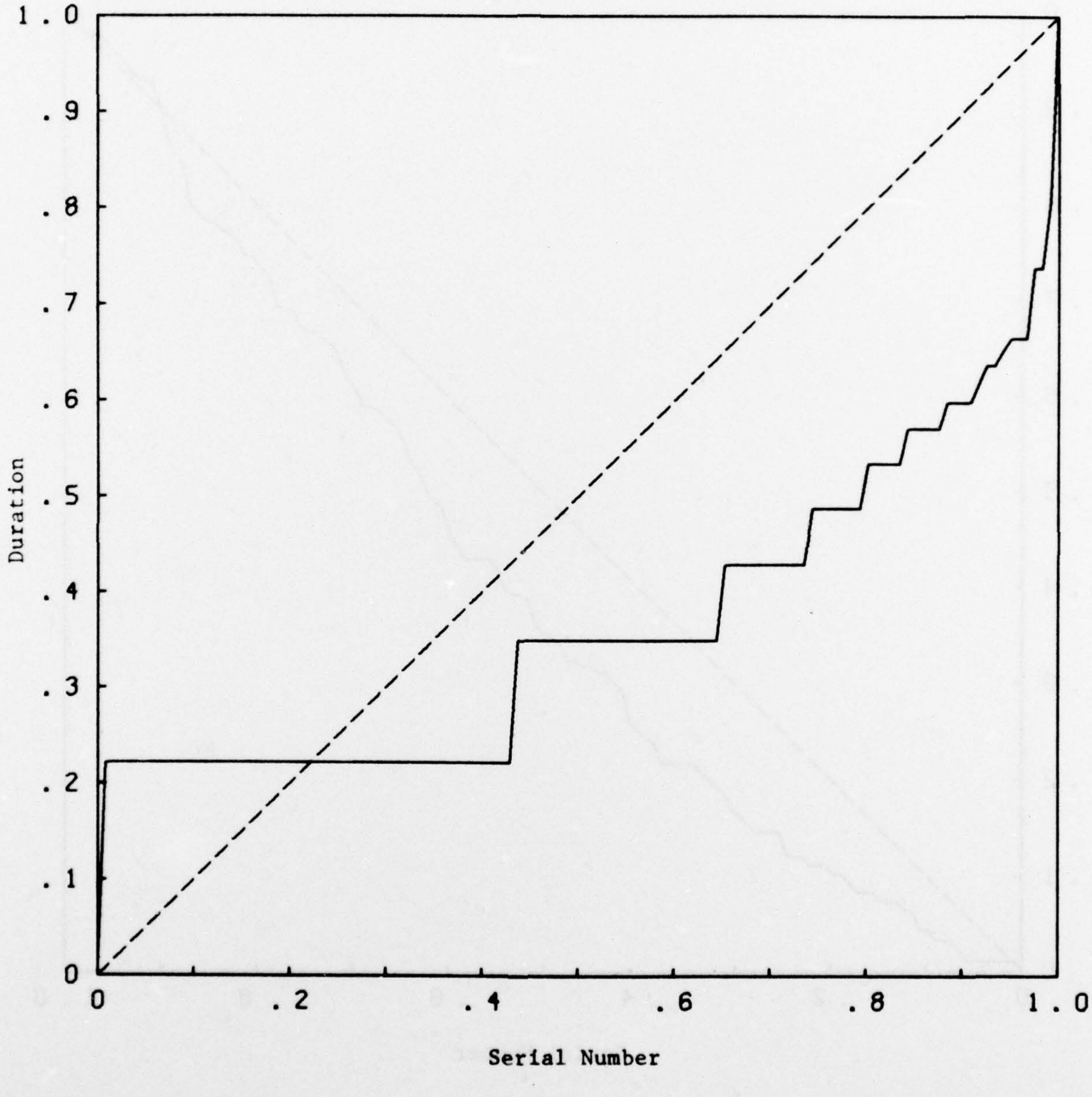
Total Time on Test Plot of Downtimes of Subsystem 3 for Mode 1

Coefficient of Variation = 2.93018



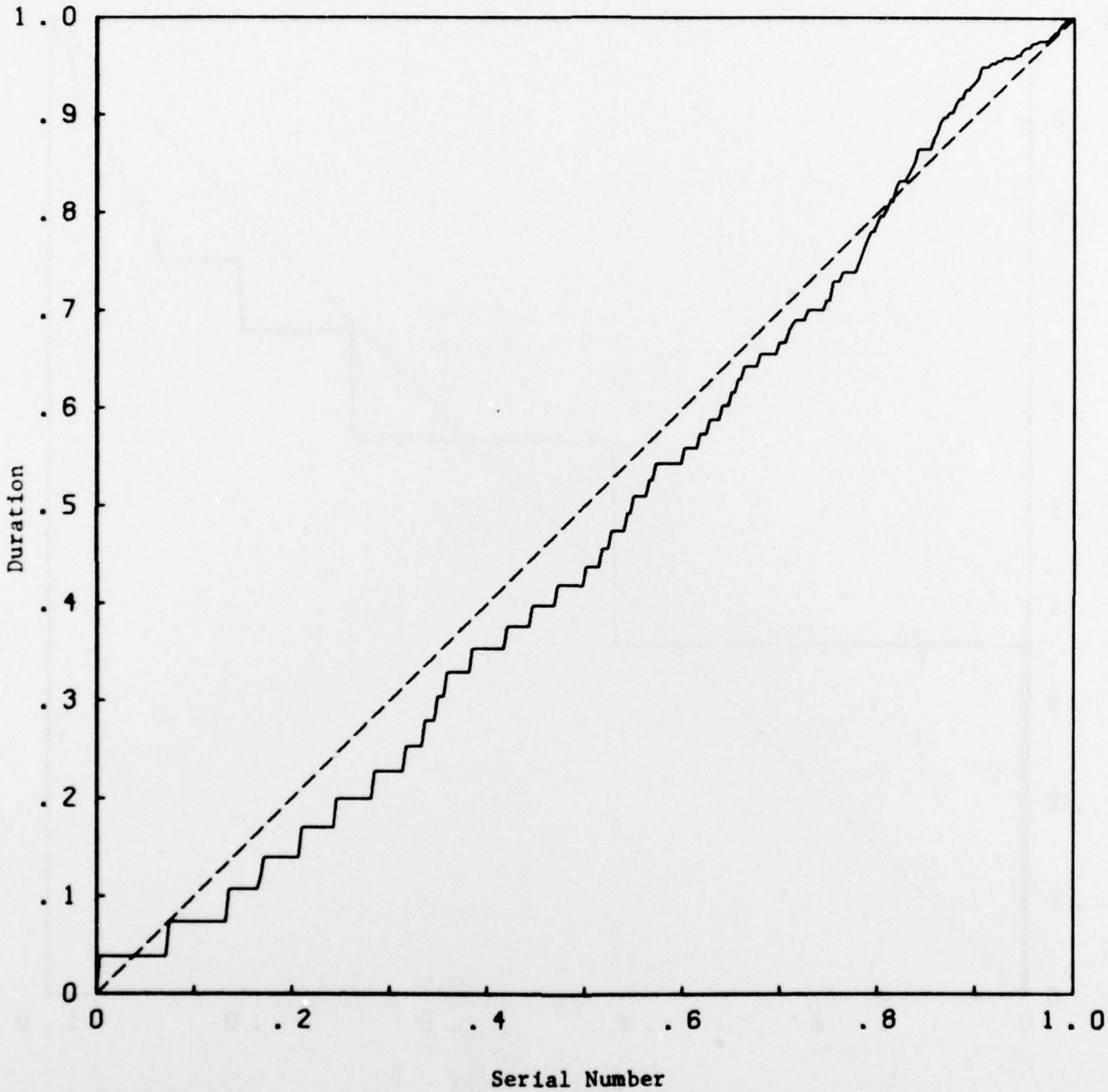
Total Time on Test of Uptimes of Subsystem 3 for Mode 2

Coefficient of Variation = 1.17043



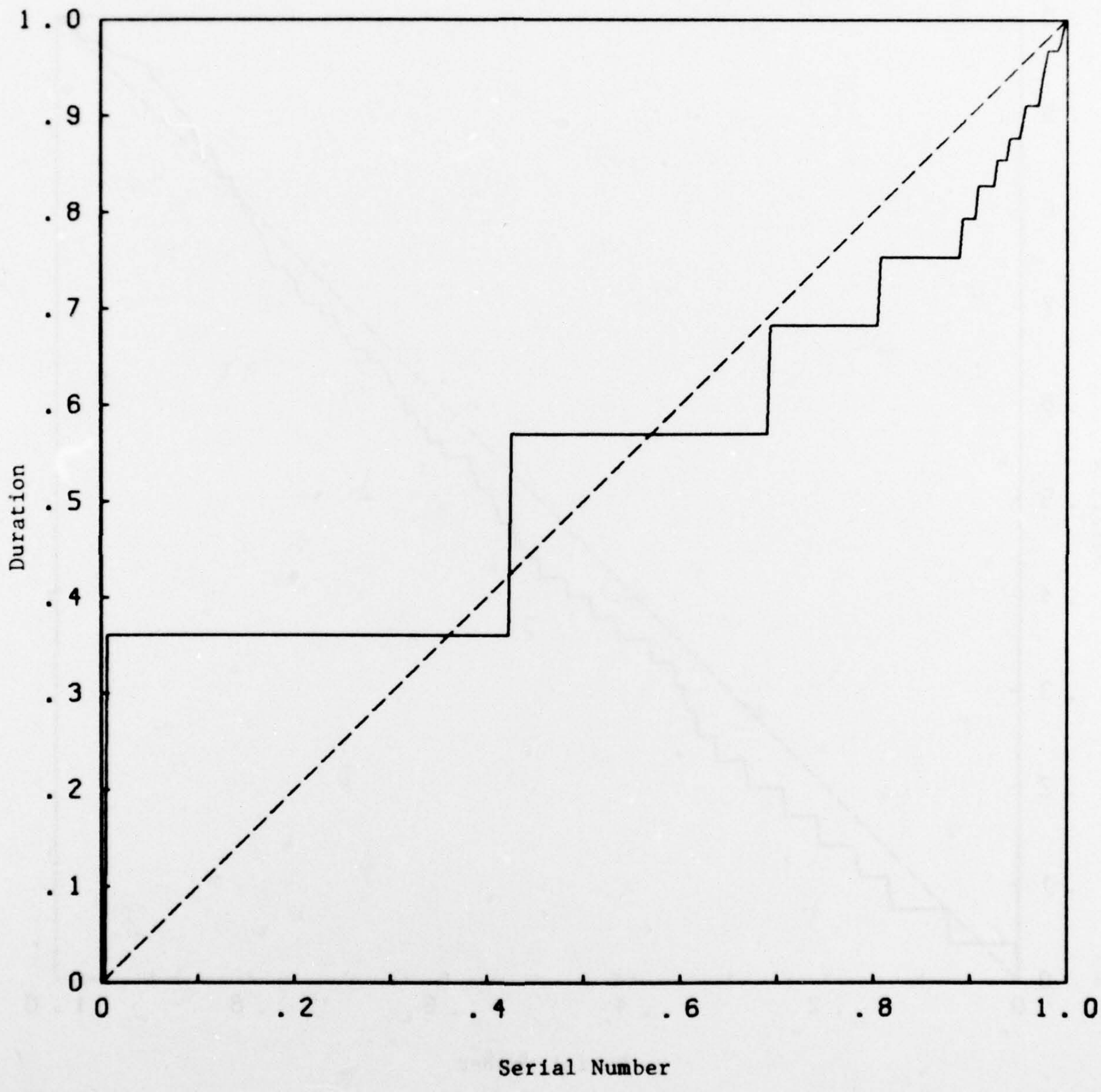
Total Time on Test Plot of Downtimes of Subsystem 3 for Mode 2

Coefficient of Variation = 3.02773



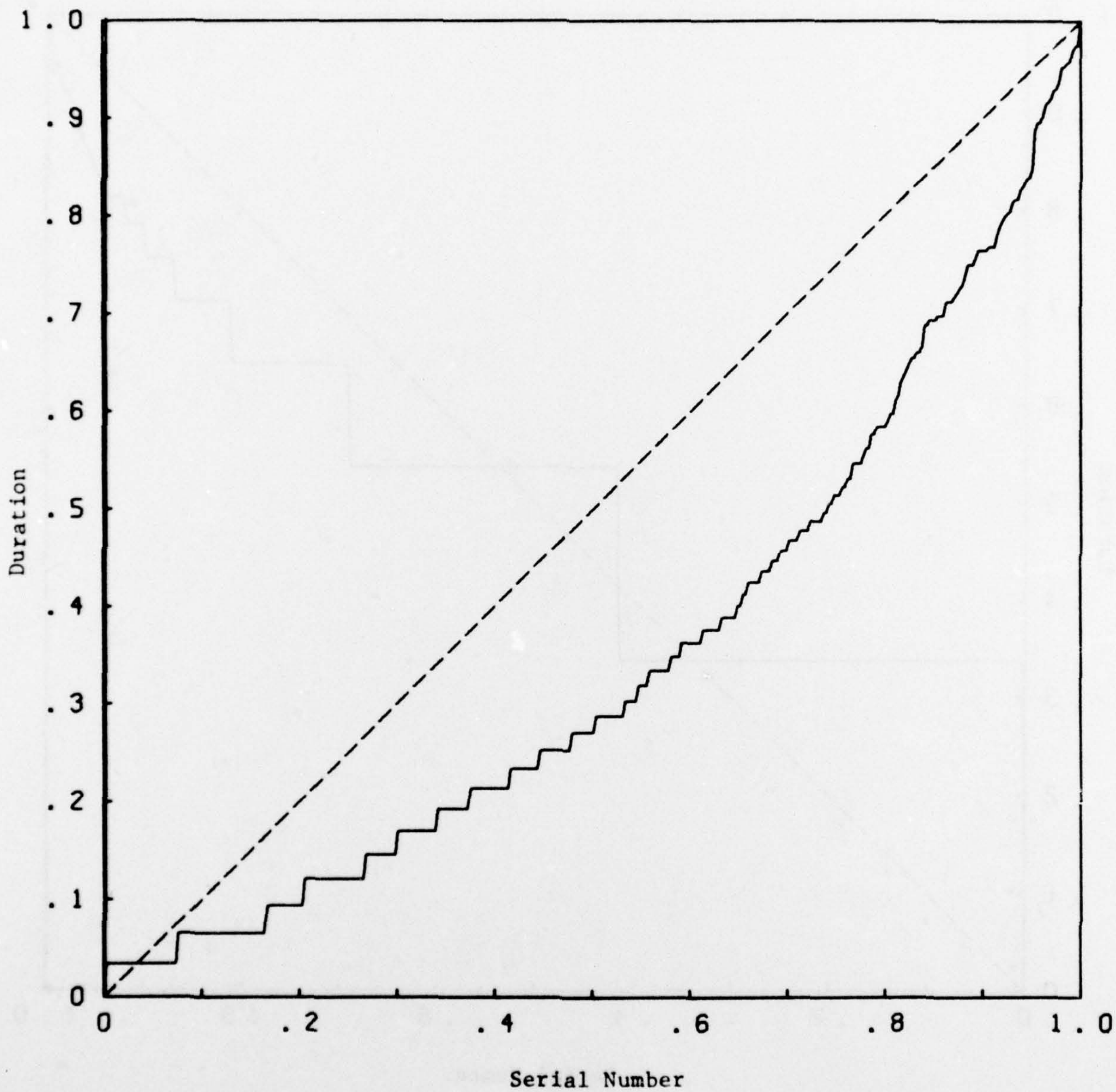
Total Time on Test of Uptimes of Subsystem 8 for Mode 1

Coefficient of Variation = 1.02252



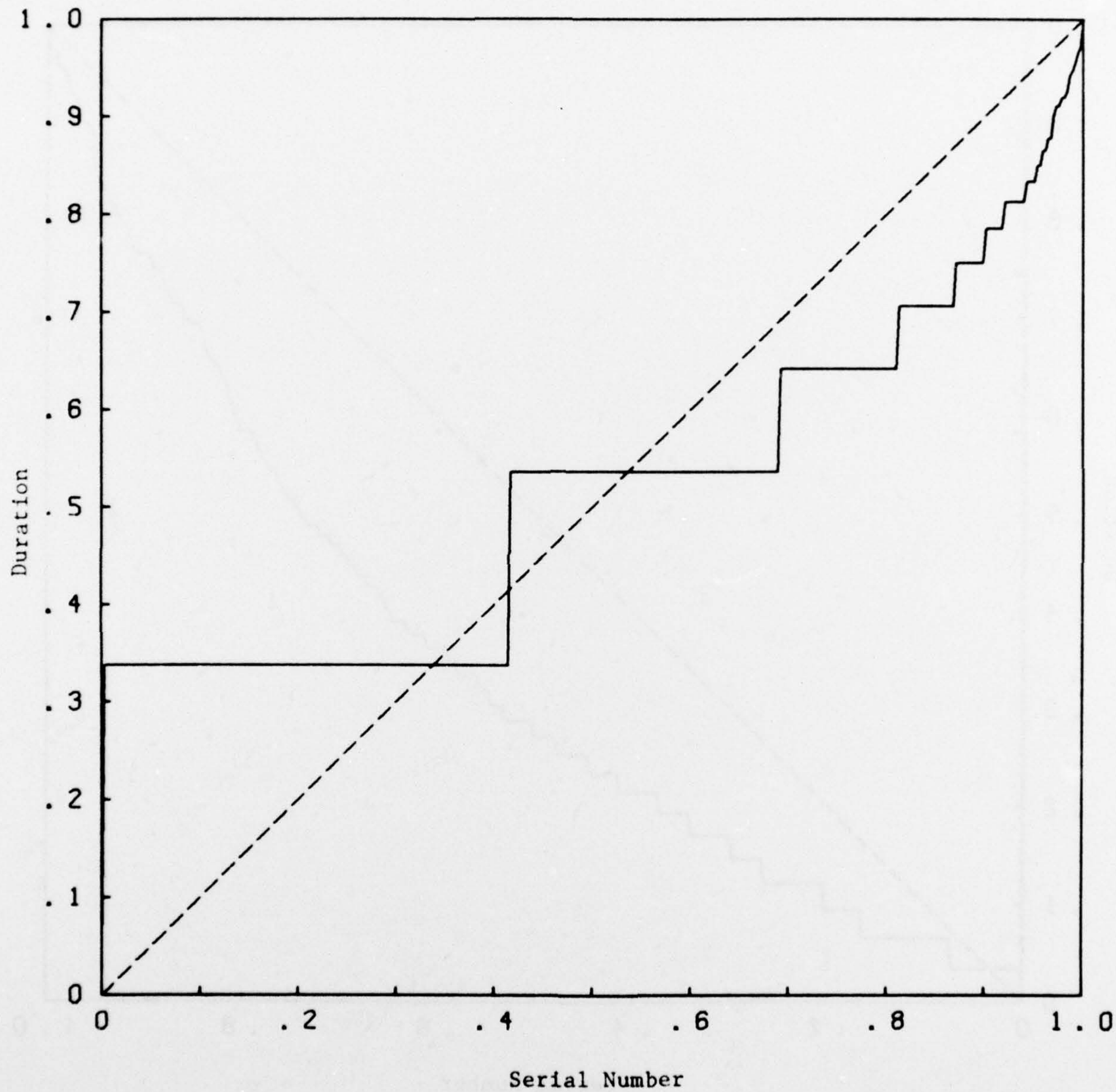
Total Time on Test of Downtimes of Subsystem 8 for Mode 1

Coefficient of Variation = 1.23465



Total Time on Test Plot of Uptimes of Subsystem 8 for Mode 2

Coefficient of Variation = 1.67861



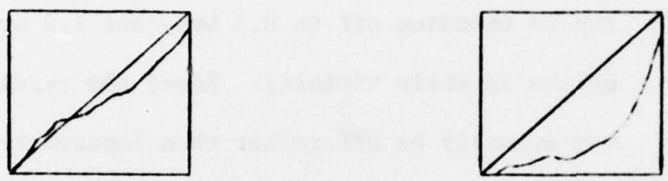
Total Time on Test Plot of Downtimes of Subsystem 8 for Mode 2

Coefficient of Variation = 1.52846

APPENDIX 4

RESULTS FROM TOTAL TIME ON TEST PLOTS

1. The following Total Time on Test Plots from ups and downs of Mode 1, 2, and 3; of subsystems 1, 3, and 8 of Mode 1; of subsystems 2, 3, and 8 of Mode 2 are typical.
2. All up time graphs are closely approximated by either (a) or (b).

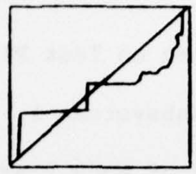


(a) (b)

(i) In case (a), the up time distribution is approximately exponential. This justifies the use of $R = A \cdot e^{-t/MTBF}$ In particular, notice that the up times of all 3 modes have a Total Time on Test Plot like (a).

(ii) In case (b), the up time distribution is either DFR, (decreasing failure rate), or (more likely) a mixture of some distributions, possibly exponentials. From people familiar with the system it is known that in some 50% of the repair cases, better designs are used to replace the failed pieces of equipment. Hence the up times following these repairs constitutes a mixed population.

3. All down time graphs are more or less like



(i) Roughly, these can be identified as lognormal.

(ii) The initial rather long flat portions of the graph are due to rounding off to 0.5 hrs. and 1.0 hrs. all points in their vicinity. Hence the repair distributions may actually be DFR rather than lognormal. This is due to the limitation of the current data-recording system, and will be remedied in the future when the data collection is computerized.